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# Emergence of energy storage technologies as the solution for reliable operation of smart power systems: A review

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ABSTRACT

The ever increasing penetration of renewable energy systems (RESs) in today deregulated intelligent power grids, necessitates the use of electrical storage systems. Energy storage systems (ESSs) are helpful to make balance between generation and demand improving the performance of whole power grid. In collaboration with RESs, energy storage devices can be integrated into the power networks to bring ancillary service for the power system and hence enable an increased penetration of distributed generation (DG) units. This paper presents different applications of electrical energy storage technologies in power systems emphasizing on the collaboration of such entities with RESs. The role of ESSs in intelligent micropower grids is also discussed where the stochastic nature of renewable energy sources may affect the power quality. Particular attention is paid to flywheel storage, electrochemical storage, pumped hydroelectric storage, and compressed air storage and their operating principle are discussed as well. The application of each type in the area of power system is investigated and compared to others.


**Contents**



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## 1. Introduction

Modern social needs and optimal generation and/or consumption of electricity beside security issues in power networks, all together, present a new concept which is so-called "Smartgrid". Smartgrid integrates advanced sensing technologies, control methods and integrated communications into current electricity network. These features optimize the operation of whole power network making objective oriented balance between the generation, demand, environment and market constrains [1,2]. The deregulation of power systems leads to remarkable changes in operational requirements. Continuous increase of the energy demand and higher regional power transfers in a largely interconnected network lead to complex and less secure power system operation. Because of economic, technical and governmental limitations, the electricity generation and transmission facilities may not cope with such requirements. At the same time, the growth of electrical loads has made the quality of power supply a critical issue. Power system engineers have been challenging with these issues to find solutions allowing the system to be operated in a more flexible and controllable manner. Since the conventional power sources (synchronous generators) are high inertial equipments, their response to any disturbances within the power system is slow and sometimes they may not be able to keep the system stable. If high-speed real or reactive power control is available, load shedding or generator dropping may be avoided during disturbances. High speed reactive power control is possible through the use of flexible ac transmission systems (FACTS) devices. To provide the power grid with the fast real power control mechanism, real power can be circulated in the FACTS devices converter. However, a more reliable solution is to quickly vary the real power without affecting the system through the circulation of power. This is where energy storage technology can play a very prominent role in order to preserve the system stability and power quality. In this case, it is expected from the storage system to relief the consequences followed by rapidly damping oscillations, abrupt changes in load, and interrupting transmission or distribution systems [3,4].

The applications of, short-time medium to high power, energy storage system (ESS) in power quality control, traction and aerospace have been reported in [5]. One of the main concerns regarding the usage of intermittent renewable resources is the fluctuation of power which is generated by this kind. The power oscillation results in the power system instability and hence damages the equipments such as generators and motors. Using ESSs would be considered as a remedy to cope with this difficulty and balance the flow of power in the power network [6–9]. ESSs are also capable of correcting load voltage profiles with rapid reactive power control and thus allow the generators to keep their balance with the system load at their normal speed. Storage entities can also utilize voltage source converters (VSCs) to interrupt current and regulate voltage for utility networks. Energy storage is now seen more as a tool to enhance system stability, aid power transfer, and improve power quality in power systems [10,11].

## 2. Energy storage systems (ESSs) applications in power system

The role of energy storage systems in increasing the stability of distribution networks have been growing day by day. The most important benefit which is come up with ESSs is to support the power grid in order to fullfil its load demand constantly [12–14]. The role of ESSs is very important in growing renewable energy systems (RESs) penetration level, controlling the frequency, upgrading the transmission line capability, mitigating the voltage fluctuations and improving the power quality and reliability. Fig. 1 shows the power magnitude and the needed time for such applications. From the end-user view of point, ESSs should be able to provide maximum power about 7.5 MW for about 100 min in order to make flatten the load profile. For the short time applications, for example, to increase RESs depth of penetration at least 1 MW for more than 30 min is required to be received by the ESSs to make sure that the use of ESSs system is reasonable.

### 2.1. Increasing RESs depth of penetration

Although RESs are environmentally helpful, the intermittent nature of some types of RESs such as solar and wind may results in the power grid voltage and frequency oscillations. This matter leads to the widespread usage and replacement of fossil-fuel sources to supply the base-load demand. In this case, integration of RESs creates some new challenges on the operation of the power system such as potential unbalancing between the generation and load demand [12,15].

To resolve the problem followed by the intermittency of RESs, there is a need to support such entities by other conventional utility power plants [12,16]. It is expected that, for every 10% wind penetration, a balancing power from other generation sources equivalent to 2–4% of the installed wind capacity is always required for a power system to maintain its stability. The use of conventional power plants for this purpose makes the system more complex than where ESSs are utilized. This is serious for countries with a large penetration of solar and wind systems such as Denmark and Spain where about 20% and 10% of the electricity generation come from wind power, respectively [12].

A huge and reliable storage capacity can provides an opportunity to highly exploit intermittent nature renewable resources in collaboration with power grids to meet the requirements for a

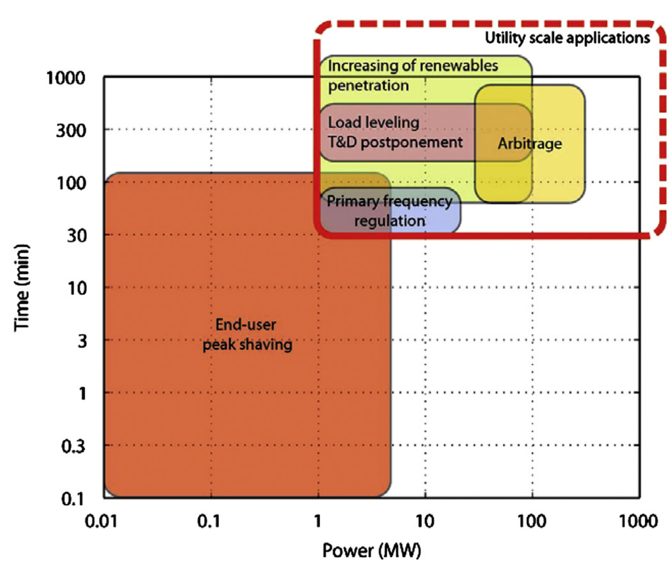



**Fig. 1.** Utility applications of ESS [12].

**Nomenclature**

| | |
|---|---|
| $A$ | effective area of capacitor plates ($m^2$) |
| A h | ampere hour(s) |
| BEV | battery electric vehicle |
| BESS | battery energy storage system |
| $C$ | capacitance (F) |
| CAESS | compressed air energy storage system |
| $d$ | distance between capacitor plates (m) |
| DFIG | doubly fed induction generator |
| DOD | depth of discharge |
| DSTATCOM | distribution static compensator |
| EES | electrical energy storage |
| EESS | electrochemical energy storage system |
| EHV | electric hybrid vehicle |
| $E_{kin}$ | kinetic energy of a rotating mass |
| EMF | electromagnetic force |
| ESS | energy storage system |
| FACTS | flexible AC transmission system |
| FESS | flywheel energy storage system |
| HTS | high temperature superconductor |
| $I$ | moment of inertia (kg $m^2$) |
| LVRT | low voltage ride-through |
| MC | matrix converter |
| NFCRC | national fuel cell research center |
| OCV | open circuit voltage |
| PHESS | pumped hydro energy storage system |
| PM | permanent magnet |
| PTES | pumped thermal electricity storage |
| RES | renewable energy system |
| RFC | regenerative fuel cell |
| SESS | supercapacitor energy storage system |
| SFES | superconductor flywheel energy storage system |
| SMESS | superconducting magnetic energy storage |
| SOC | state of charge |
| STATCOM | static synchronous compensator |
| UPS | uninterruptable power supply |
| VBR | valve regulated battery |
| VLA | vented lead acid |
| VRFB | vanadium redox fellow battery |
| VRLA | valve regulated lead acid |
| $\varepsilon_0$ | permittivity of vacuum (F/M) |
| $\varepsilon_r$ | relative permittivity of material between capacitor plates (F/M) |
| $\omega$ | angular frequency (rad/s) |

more sustainable future [17–19]. To design reliable power grids which include in both conventional and renewable energy based generation plants, it is essential to propose proper storage systems with adequate capacities providing continuous power (e.g. from 1 to 100 MW) for hours.

In [9], a simple probabilistic method has been introduced to predict the proficiency and to measure the effectiveness of an energy storage system in increasing the penetration level of intermittent RESs where the electricity grid is weak. The value of generated power through time-shifting delivery has been also enhanced. The interconnection of wind RES system has been investigated in this paper where the voltage rise index can limit the size of RESs. It has been proven that the long-term storage system (up to one day) is more advantageous than the short-term one (less than 1 h) since in the latter case a small increase in the amount of generated electricity can be absorbed by the power grid. However, the long-term storage systems are much more costly solutions than the short-term ones.

### 2.2. Load leveling and peak shaving

Load leveling refers to the use of electricity in on-peak (high demand) periods trough the electricity which can be stored during off-peak (low demands) periods. Moreover, ESSs level the amount of power which can be drawn from the power grid during seasonal, weekly, daily, hourly and even transient changes in load demand. In addition, there are two options to supply a growth in load demand, the first is to increase the infrastructure and the generator capacity and the second is to install energy storage units. ESSs also remove the need to set up new infrastructures, such as new power lines or feeders, where a new load demand is added. RESs which are not confined by their geographic intermittent nature can be also suitable candidates for load leveling purposes [12,20].

Peak shaving may refer to the operating policy applied for the storage devices to store cheap electricity during the off-peak demand period and in order to cell back the stored energy to the grid during the high demand. Normally, the peak shaving process is taken place within the time frame of 1–10 h [21]. Suitable candidates for peak shaving applications are batteries, flow batteries, CAESSs and PHESSs. Regarding the batteries, numerous techno-economic studies have been done which display the feasibility to store energy during off-peak demand hours and sell it at peak demand periods [20,22]. In [23] a techno-economic study has been conducted to investigate the viability of wind–hydro systems in providing power during peak load demand periods. The results show an excellent technical and economic performance. It can be concluded from this paper that the integration of wind power plants in the isolated study case can be increased by 9%, allowing to a penetration level of 20%. A significant reduction of $CO_2$ emissions through the use of PHESS installations instead of using fuel peak power plants is also highlighted in [24]. However, in the case of operational dynamic security issues, the system operation, it is useful to add some more technologies in order to provide spinning reserve to the system [25].

Depending on the duration and variability, several undesired grid voltage effects at the end-user level can be determined. Such impacts are divided in four types, namely, long-period interruptions (blackouts), short-period interruptions (voltage sags), voltage peaks, and variable fluctuation (flicker). To perform peak shaving and prevent against blackouts, a suitable solution is to install UPS systems. If an online UPS is installed in series isolating the load from the grid, fluctuations produced by the utility have no effect on the users. However, this solution may not be optimal for all applications. In [17], a method is presented for grid voltage stability. This method alleviates the effects of voltage drop by providing additional reactive power and injecting real power for a time interval of up to 2 s. The energy storage capacity which is required to protect the load against this voltage degradation is low. In applications with ride-through capability, the energy storage demanded is even lesser because a part of the load demand can be supplied by the grid [12].

The voltage flicker can be considered as a result of rapid changes in RESs generations and industrial or domestic loads such as rolling mills, electric arc furnaces, welding equipment, and pumps which can be operated periodically. An ESS can support the system to decrease voltage oscillations which are generated by such a kind of loads and/or generation units. Lower energy storage

devices e.g. super-capacitors [27,28] and batteries can also support the system to manage the active power demand where a STATCOM which includes BESS or FESS may compensate for the reactive power demand [29,30].

### 2.3. Frequency regulation and damping out the oscillations

System stability aspects are usually investigated through modal and frequency domain analysis and hence frequency is an important parameter that should be kept within the allowed boundary. Electronically interfaced distributed generators are normally low inertial generation units. If ESSs are not utilized together with ESSs, during the transients any changes in the system states may result in uncontrollable oscillations and force the system to become unstable. To adjust the grid frequency dynamically during the transients, ESSs can play a key role to keep stable the frequency and hence to increase the stability of system. Since the frequency adjustment highly depends on injection and absorption of real power within a short duration (1–2 s), low and medium energy storage devices can be exploited to stabilize the angular frequency [26]. For instance, this application may contribute to the frequency stability of isolated utilities based on diesel generators which is addressed in [31]. Flow batteries, batteries, and short time ESSs like super-capacitors, flywheels and superconducting magnetic energy storage systems (SMESSs) are well-suited for this application. Flywheels are the proper candidates which can be exploited to improve the dynamic performance of power network undergoing disturbances [32,33]. In [34–37], typical SMES systems have been considered in order to study how quickly they can supply large quantities of active and reactive power demands at the same time. In these studies, wind power plants together with SMES are supposed to be responsible for damping out power flow oscillations. The technical impacts of adding storage systems on improving the system stability have been experimentally tested in [38]. This study confirms that the controller allocated to dampen the power oscillation is more robust, than the system without ESS, against changes in power system state only if the flow of active and reactive powers is managed by means of SMESS along with BESS.

### 2.4. Operating reserve

In an electrical power grid, the operating reserve refers to the generating capacity which is available and can be injected to the system by the operator decision within a short period of time. Operating reserve is supposed to meet demand in case of loss of main supply or any other reasons which may result in the net exchanged power is not to be zero. Most of power systems are designed in such a way that, under normal conditions, the operating reserve is always equal to at least the capacity of the largest generator plus a fraction of the peak load [39]. The operating reserve consists of the spinning reserve as well as the non-spinning or supplemental reserve. Spinning reserve is defined as the unused capacity that can be activated according to the operator's decision, which is provided by synchronizing with the network devices capable of affecting the active power of the system [40]. The non-spinning reserve or supplemental reserve refers to the extra generating capacity that is not currently connected to the system but can be brought online after a short delay. In isolated power systems, this typically equates to the power available from fast response generators. However, in interconnected power systems, this may include the power available on short notice by importing power from other systems or withdrawing the power that has been already being injected to the system.

Secondary and tertiary reserve can be considered as the spinning reserve because they can be also activated by the operator's decision. Energy storage technologies which are well-suited for this application are flywheels, SMES, batteries, flow batteries, CAES or PHS installations [21]. In isolated systems like an islanded RES [41,42], the use of energy systems can play a key role in order to maintain the stability of system. In [32], a BESS is suggested in order to be exploited together with an isolated wind–hydro–gas system. VRBs are also very suitable candidates for this application because they can shortly response to any changes in the net power demand as well as they have the capacity of being overloaded [43].

### 2.5. Low voltage ride-through (LVRT) capability

Low voltage ride-through is a problem when a nearby grid fault causes a reduction in the grid voltage at the point in which the generator is connected to the grid. This limits the power that can be extracted from the device. If there is large input power, and the powers are not controlled, the power imbalance leads to an unregulated increase in the turbine speed, or dc bus voltage of the back-to-back converter. ESSs could prevent turbine over-speed, stabilize dc-bus voltage level, and hence satisfy the grid requirements. ESSs which can be suitable for this application are super-capacitor bank, flywheel, and SMES.

In [44], the ability of an ESS to improve the performance of a DFIG-based wind generator has been assessed. The dc-link of a back-to-back converter, which is connected to a DFIG wind turbine, is connected to a supercapacitor. The improved LVRT capability has been reported as the output power is considerably smoothened. The storage device can effectively handle the situations coming up with ride-through disturbances and hence exhibit perfect characteristics during and subsequent to such voltage events.

### 2.6. Power quality improvement

ESSs are useful to maintain the voltage within the allowed boundary ($\pm 5\%$), which is specified in [45], and hence to generate high quality power, it is mandatory to control the reactive power flow in the power network accurately. The use of ESSs can also improve the dynamic behavior of the generation units connected to it such as wind turbines where these generators are supposed to be operated as voltage compensator units [46]. Since high adequate ramp rate is required to response to the variations in power demand, batteries and short-time energy storage devices such as supercapacitors and flywheels, and SMES can be suitable solutions for this application. In [47], a very fast absorption and injection by the SMES has been reported. Energy storage devices can be also connected to FACTS or DSTATCOM [48] devices, as a source of power which connected to a dc-link, and compensate for the active and/or reactive power unbalance within the system. In addition, for the purpose of eliminating harmonics within the system ESSs can be exploited to compensate for the reactive power and improve the power quality [49].

### 2.7. Applications in microintelligent power grids

The importance of smarter power network has made a big challenge in today power grids where the renewable energy sources are supposed to be used as the prime movers and their duty is to keep stability and enhance the performance of system. This act can be simply done through small amounts of energy stored throughout the grid. All elements of design from demand response techniques in homes to dynamic loading of transmission lines based on temperature and wind speed will come up through a

proper smart grid design [2]. Smart grid concept is a broader definition of microgrid systems. Several microgrids that can be interconnected to a power network may form a smart grid and the relationship between them and the main supply can be determined in such a way that the whole network performance improves in terms of the cost, reliability, environment and security.

A microgrid system is defined as an integration of electrical loads and generation [50]. As shown in Fig. 2, the generators in the microgrid system may be any of various kinds, such as microturbines, fuel cells, reciprocating engines, or any of renewable power resources such as PV and wind. Microgrid can be isolated from the utility to keep service reliability. Distributed generation and storage (distributed resources) units are essential components in the microgrid to provide the microgrid load demand with adequate power. The major benefit of installing a grid-connected distributed resources system is the assurance of receiving power from the utility when the system is not running and hence this is necessary for renewable intermittent energy resources like solar and wind and for generation units that have to be shut down for cyclic maintenance. While some customers use distributed generation devices as a primary source of power, others may exploit them as backup generation for critical electric loads when the utility cannot provide power due to storms, blackouts, or other unexpected events.

To ensure uninterrupted supply to critical loads, an energy management unit is required to control the operation of energy storage devices. In fact, successful operation of the microgrid highly depends on proper operation and control of the storage devices during contingencies and disturbances. As electronically interfaced microsources have low inertia or ride-through capability, storage devices can be also helpful to enhance the microsource performance during low voltage transients, motor starts or other short-term overloads, especially for islanded operation. Storage devices are generally DC voltage sources and hence to generate AC power, they should be connected to a DC/AC conversion unit (inverter). Adversely, flywheel generators directly generate AC and hence might directly feed the microgrid bus. Storage devices must be able to respond rapidly to any changes in load demand and this

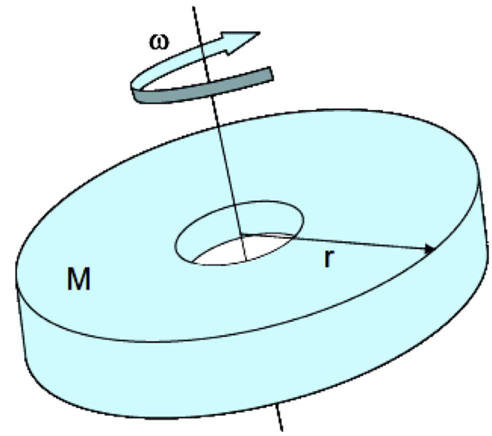



**Fig. 3.** Physical factors in energy storage capacity [26].

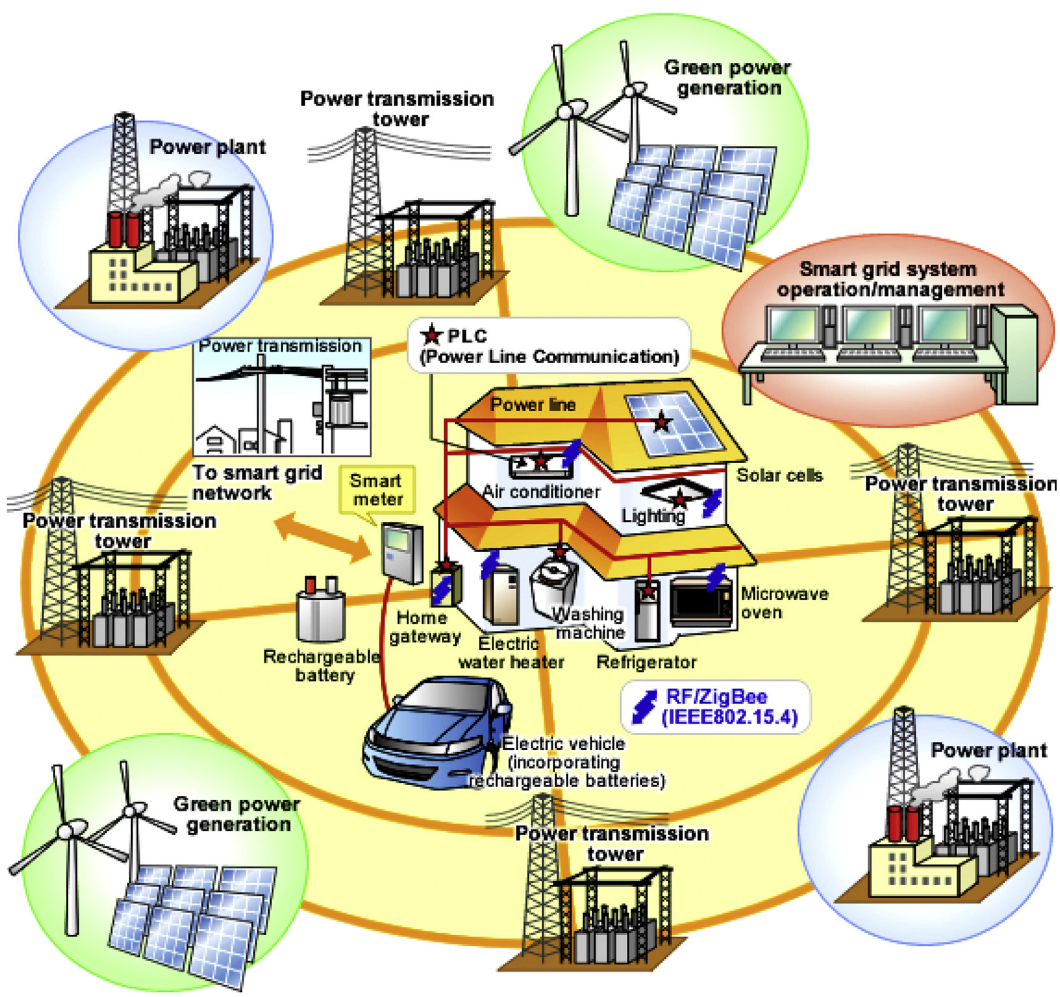



**Fig. 2.** A typical intelligent micro power grid along with distributed resources and management units.

burden should be managed by their own local controllers instead of depending upon supervisory channel commands. Some storage devices like capacitors might store power at high density but are restricted to short-term discharges, whereas some like flywheels suffer from low power density but can be discharged over a longer time period [51].

## 3. Energy storages systems (ESS) technologies and considerations

### 3.1. Flywheel energy storage system (FESS)

A mass which rotates about an axis is called flywheel. Energy can be stored mechanically in angular momentum of the rotating mass in the form of kinetic energy. Basically, the operation of flywheel is divided in two parts. First, when the energy should be stored in the flywheel mass, it accelerates through a motor which is connected through its shaft. Second, during the deceleration, the rotational mass speed declines and the motor operates in generator mode discharging the stored energy back into the power grid. According to above mentioned definitions, flywheels are always operating between these two modes to balance supply and demand keeping tuned the power grid at its nominal frequency of operation [52]. The flywheels are capable of switching from the full generation mode to full absorption mode in a few seconds. This advantage enables them to deliver the electrical energy at least twice as much as the electrical energy which is produced by a typical natural gas-fire power plant while reducing the carbon emissions to half [52]. Also, this rapid response nature of flywheel systems brings the ability of resolving the problem of short-term transients caused by sudden changes in power system loads. For example, the problems such as voltage drop which may lead to a power outage [53].

To understand the physics of flywheel, a good understanding about its governing mathematical equations is required. Kinetic energy can be appeared in any moving subjects. The rotational mass like flywheel is not excepted from this general rule when rotating. The kinetic energy which is generated during the flywheel rotation [53] can be expressed according to Eq. (1).

$$E_{kin} = I\omega^2 \quad (1)$$

where $I$ is the moment of inertia and $w$ is the angular speed.

The moment of inertia can be also equated as Eq. (2).

$$I = \int \rho(x) r^2 dx \quad (2)$$

where $\rho(x)$ is the mass distribution and $r$ is the radius of flywheel body as shown in Fig. 3.

The larger rotational speed and moment of inertia result in the generation of more kinetic energy. The rotational speeds can be very high ranging from 20,000 to 100,000 rpm. Special attention (due to the huge centrifugal force which is given in bellow equation) should be given to the strength of the material [53] which is used to fabricate the body of flywheel based on Eq. (3).

$$\text{Force} = (\text{mass})(\text{acceleration}) = mr\omega^2 \quad (3)$$

Nowadays, flywheels are designed and manufactured in such a way that enables them to store a value of energy up to about 125 Wh kg$^{-1}$ having a capacity above 2 kWh. One of the key strategies in designing the flywheels is to design the body so that the stress on the mass becomes similar in all directions. If the

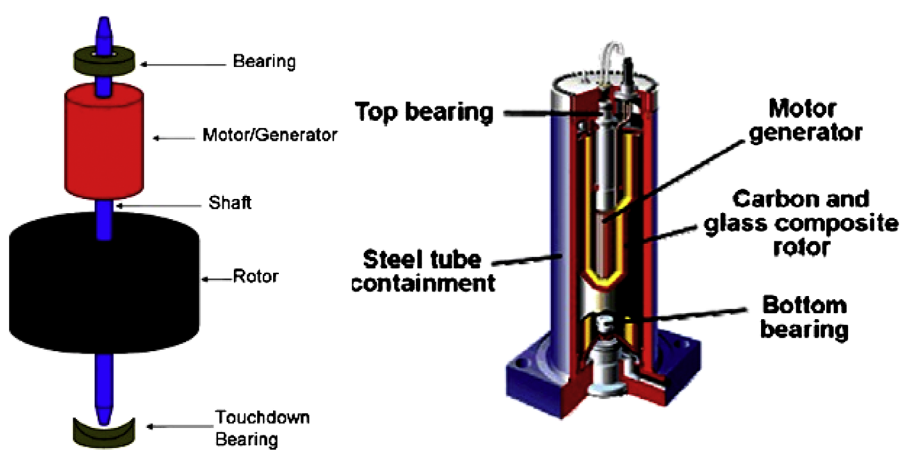



**Fig. 4.** Critical components of a typical flywheel storage system and its cross-sectional view [132].

**Table 1**
Main characteristics of the electrical machines suitable to be used for FBESS [55].

| Machine | Asynchronous | Variable reluctance | Permanent magnet synchronous |
|---|---|---|---|
| Power | High | Medium and low | Medium and low |
| Specific Power | Medium (0.7 kW/kg) | Medium (0.7 kW/kg) | High (12 kW/kg) |
| Rotor losses | Copper and iron | Iron due to slots | None |
| Spinning losses | Removable by annulling flux | Removable by annulling flux | Non-removable, static flux |
| Efficiency | High (93.4%) | High (93%) | Very high (92.2%) |
| Control | Vector control | Synchronous: vector control. Switched: DSP | Sinusoidal: vector control. Trapezoidal: DSP |
| Size | 1.81/kW | 2.61/kW | 2.31/kW |
| Tensile strength | Medium | Medium | Low |
| Torque ripple | Medium (7.3%) | High (24%) | Medium (10%) |
| Maximum/base speed | Medium ( > 3) | High ( > 4) | Low ( < 2) |
| Demagnetization | No | No | Yes |
| Cost | Low (22€/kW) | Low (24€/kW) | High (38€/kW) |

flywheel gets out of the balance, it can be dangerous and hence their components are intentionally made of small particles. The large units normally are placed in underground being protected by a robust steel cover. More information about the different varieties in the flywheel shapes and materials is described in [53].

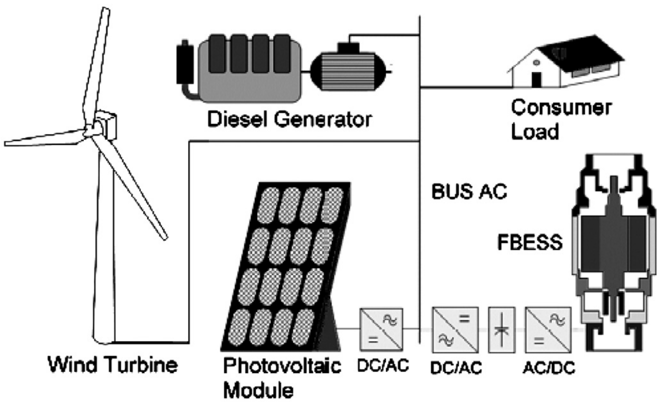



**Fig. 5.** An example of cogeneration between distributed generation resources.

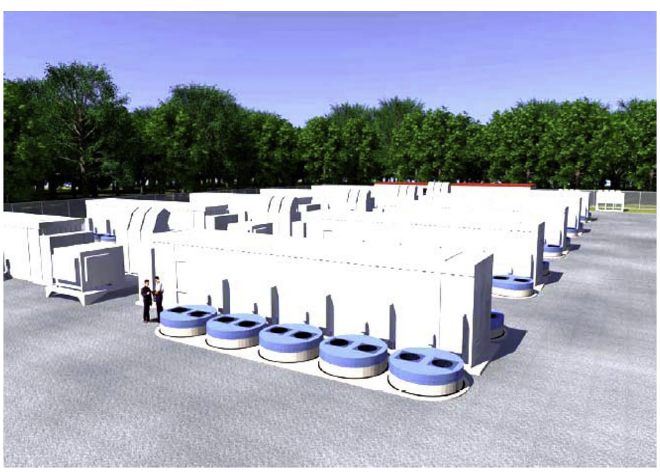


**Fig. 6.** North America large scale flywheel energy storage installations for utility application [58].

As a problem, flywheel systems have a wide boundary of rotational operating velocity (variable frequency). It makes them complex in both design and fabrication stages especially in coupling with mechanical structures and frequency adjusting electronics circuitries [54].

A real flywheel system produces an amount of heat in its rotor during the rotation. This heat is generated as a result of friction between the flywheel and the surrounding environment, the bearing of rotor and its supporting structure, and from the strains and stresses within the rotor itself. This high temperature should be kept in an allowed boundary. To remove this heat, there are some methods which taking one of them may deprive the system to take the advantages of the others. Thus, a trade-off strategy should be adopted between the methods in order to choose the best solution [26].

As shown in Fig. 4, the structure of a typical flywheel system is composed of several critical parts which can be divided as explained in the followings [26]:

- *Rotor*: which is the main part of flywheel storing energy while rotating.
- *Bearings*: components that support axis of the rotor to spin remaining on a fixed position.
- *Generator/motor*: which transforms the kinetic energy stored in the rotor to electrical energy which should be consumed by the power grid and vice versa.
- *Power electronics interface*: which tunes and controls the output/input voltage and frequency of the generator/motor.
- *Instrumentation and monitoring*: which monitor the state of flywheel to make sure that it is operating within design boundaries.
- *Housing*: a chamber around the flywheel which maintains vacuum around the flywheel and protect against hazardous mechanical destructions and failures.

There are two types of electrical machines i.e. the axial-flux and the radial-flux permanent magnet machines. These are used together with diodes to dispatch DC power into an inverter unit. The inverter unit which is a power converter uses pulse-width modulation (PWM) technique to generate AC current from that DC power which is produced by diode rectifier unit. Using the power converter gives more flexibility to control the flow of power from the flywheel to the power grid and vice versa. Power converter can be equipped with LC filter at their terminal. It makes possible to

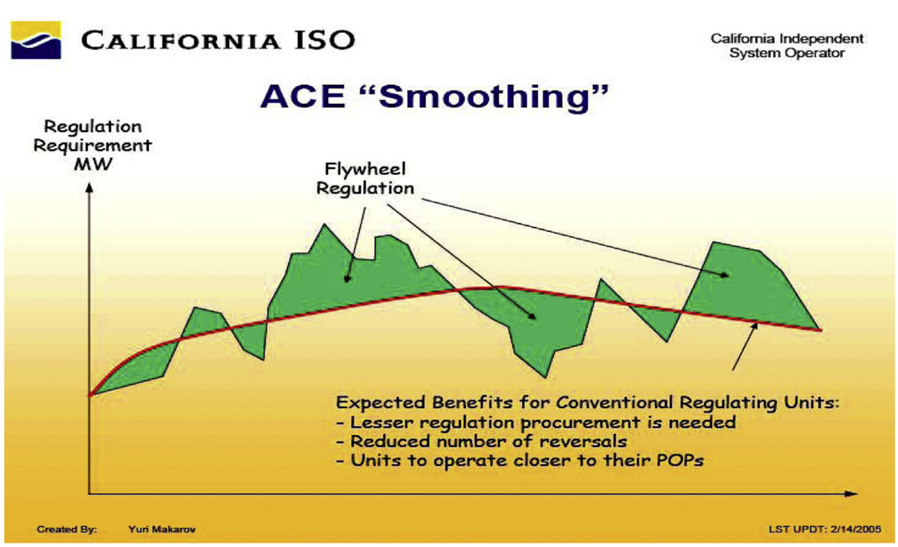



**Fig. 7.** Instantaneous area control error (ACE) strategy to regulate the load profile [58].

provide the power grid with a clean waveform eliminating the presence of harmonics which brings many concerns regarding the increase in losses, EMI and deterioration of winding [5,55].

However, permanent magnet machines are in exposure of sudden demagnetization which results in increase of their temperature. These types of electrical machines are expensive and low tensile strength. To cope with this problem, variable reluctance machines are recommended since they have no demagnetizing characteristic and they produce the torque through the variation of reluctance. Also, in high power applications, it is possible to use asynchronous machine because of their high torque, low cost and rough structure. Using doubly fed asynchronous machineries also permits reducing power electronics sizing. The characteristics of machine interfaces are summarized in Table 1 [55].

Nowadays, the application of FESS has got much attention in the area of power system stability and reliability studies. For example, to manage the short-term fluctuations in generated power by wind turbines (due to the non-dispatchable nature of wind resources), a DSTATCOM system (a fast response solid state power controller) can be connected from its DC-link (DC Bus) to a FESS. This configuration brings some advantages for the power network e.g. declination of voltage and power fluctuations during the transients [56].

To mitigate the fluctuations in power generated by wind and solar (non-dispatchable resources) systems, FESS can be utilized. In this case, during the sunny and/or windy moments the additional energy is stored in FESS while during the moments when the wind blows slowly and/or the solar radiation is low, the stored energy is fed back into the power grid (peak shaving application). Fig. 5 shows the collaboration (cogeneration) between distributed energy resources including wind, solar, diesel and flywheel storage in supplying power to a local load. The presence of FESS in this configuration is advantageous since it reduces the number of unnecessary start/shut-down cycles applied to the diesel generator while increasing its lifetime and declining emissions together with the consumption of fuel [55]. FESSs are also effectively useful to compensate the long duration voltage drops in power systems providing the consumers with high energy density and low cost [57]. Flywheel systems are also very fast response in nature so they can be helpful where rapid frequency adjustment resources are required [2].

In North America [58], as shown in Fig. 6, a large scale (20 MW) flywheel storage system is being presented to provide the power grid with a frequency regulation facility. To analyze the operation of this system, technically and commercially, the operating data for 18 months have been recorded. The dispatching data have been extracted using ISO algorithms. Fig. 7 identifies the strategy exploiting the algorithms which dampen the signal measured by instantaneous area control error to obtain an acceptable generators transient response. The field data confirms that the performance of this system is superior when dealing with cost, emissions and operational constraints.

Another research which has been conducted by California energy commission (CEC) confirms that the aforementioned flywheel energy storage system is always able to track and regulate the system frequency in shortest possible period of time. Fig. 8 demonstrates a comparison of regulation effectiveness between flywheel and other types generating plant in the US [58].

#### 3.1.1. Flywheel energy storage systems applications

*3.1.1.1. Wind-diesel generator with a flywheel energy storage system.* The comparative study for flywheel system in an isolated wind plant was done by Carrillo et al. [59]. The result of this study is hydrostatic transmission (HT) based on the variable speed flywheel system. The schematic view for flywheel connected to a synchronous generator and diesel engine are given in Fig. 9. They proposed the system on the basis of simulation result of almost constant speed flywheel, a variable speed one based on a power electronic converter. The variable speed configurations have a more appropriate behavior against wind speed variations. However, the almost constant speed configuration has the best response against load variations. A doubly fed variable speed wind induction generator connected to the grid associated to a FESS was investigated by Ghedamsi et al. [60]. They studied the dynamic behavior of a wind generator, a DFIG, and the power control of the system. The overall dynamic performance of the system showed that the matrix converter (MC) is technically a viable alternative between the conventional

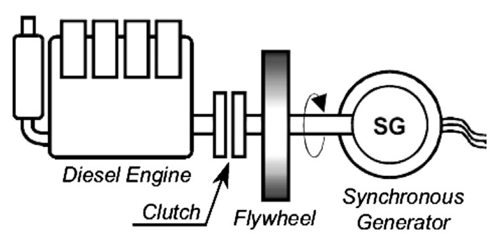



**Fig. 9.** Flywheel connected to a synchronous generator and diesel engine.

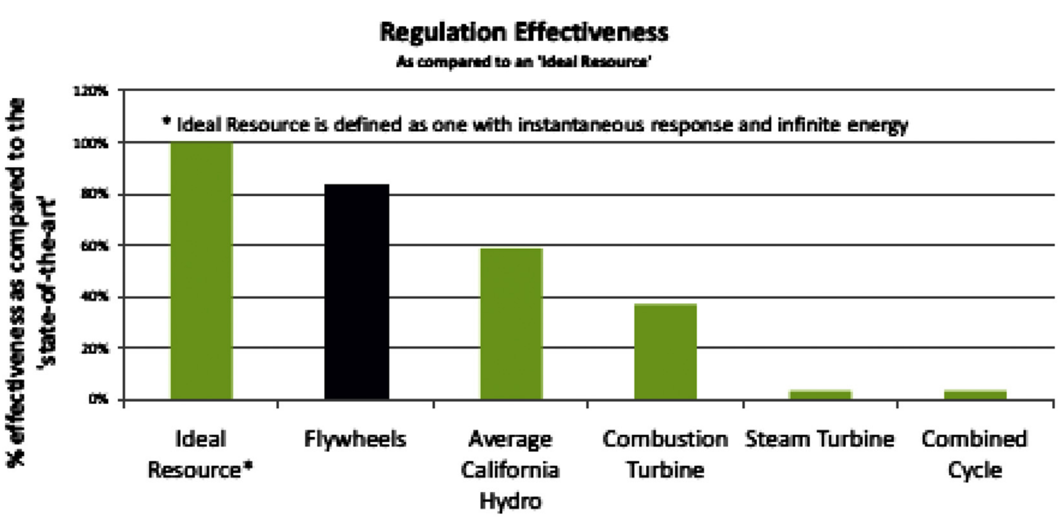



**Fig. 8.** Fast response technologies can reduce the amount of regulation procurement required up to 40% [58].

ac–dc–ac converters which are used as interface unit for the wind power plants.

*3.1.1.2. Flywheel rotor for energy storage system.* Flywheel rotor design is the key of researching and developing flywheel energy storage system. The general design method of flywheel rotor for energy storage system was discussed by Han et al. [61]. They have determined flywheel rotor parameters of 600 Wh flywheel energy storage system. The steel or metallic hub of composite material was used for flywheel, which was made of the isotropic and ductile materials. They found that the maximum stress is always at the inner radius of the flywheel rotor and the maximum outer diameter decreases if the inner diameter is increased. The design of flywheel rotor prototypes to enhance the rural electrification in sub-Saharan Africa was developed by Okou et al. [62]. The flywheel rotors were made by locally available fiber and epoxy resin. The test was conducted on the flywheel rotor profiles together with an axial flux permanent magnet machine and it was able to store 227 kJ of energy. They also analyzed for life cycle cost and compared to the energy costs between a lead acid battery system and a flywheel rotor system. The result showed that by integrating the flywheel system into solar home systems, a cost saving of 37% per kWh for rural system installations could be achieved.

Tsukamoto and Utsunomiya [63] also proposed a FESS with rotor shaft stabilization system using feed-back control of the armature currents of the motor-generator. In this system, the rotor shaft has a pivot bearing at one end of the shaft and a high temperature superconductor (HTS) bulk bearing (SMB) at the other end. The losses in pivot bearings were smaller because the pivot bearings need to sustain only small forces. The developed method can be applied to a large scale FESS. The superconductor flywheel energy storage system (SFES) using a piezoelectric actuator was also developed by Jang et al. [64]. The SFES has only disadvantage that electromagnetic damper is needed because superconducting bearings do not have enough damping coefficient. The damping feasibility test was conducted with a 300 μm gap between the permanent magnet (PM) and HTS bulk with a PM vibration of 30 μm. For the actual SFES test, the gap between the PM and HTS bulk was 1.6 mm and the PM vibration was 25 μm. The following conditions were conducted to optimize an appropriate voltage input to the lower vibration exciter or a displacement of piezoelectric actuator and an appropriate phase difference. Therefore, this experiment proved the feasibility of creating a damping effect using the piezoelectric actuator. The results of this experiment will be very useful for the stable operation of SFESs and can be used for fundamental studies of the application of a piezoelectric actuator as a damping system in various superconducting applications.

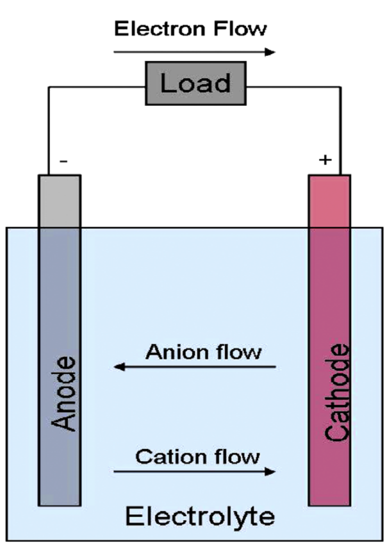



**Fig. 10.** Flow of charge carriers (ions) which finally leads to flow of current through the external circuit [132].

*3.1.1.3. Flywheel energy storage system for batteries and High power UPS system.* The FESS can be used to store and release energy in high power pulsed systems. Based on the use of a homopolar synchronous machine in a FESS, a high performance model based on power flow control law was developed by Amodeo et al. [65]. This law is derived on the basis of voltage space vector reference frame machine model. They observed for the torque angle and rotor speed and implemented it for a sensor-less control strategy. Prodromidis and Coutelieris [66] studied for feasibility of a standalone renewable energy system (RES) to supply the electricity using a FESS. They used flywheels in parallel connection with electrochemical batteries as an integrated storage device in the same power plant. It was found that an off-grid project using advanced and totally "green" technologies is possible and comparable to more conventional renewable energy based systems in terms of energy and economical feasibility. Finally, they concluded that systems with low price flywheels are equivalent to those with electrochemical batteries.

### 3.2. Electrochemical energy storage systems (EESS)

The oldest energy storage technology for power system applications are electrochemical energy storage systems (EESSs). They can be divided in three groups, namely, primary batteries, secondary batteries and fuel cells. The common characteristic of such devices is their ability in transforming stored chemical energy to electrical energy. The difference between fuel cells and batteries is that the fuel cells store the energy which is supplied from an outside substance such as hydrogen, methanol or hydrazine while batteries store the energy using an embedded material. Primary batteries are those that cannot be recharged once the chemical inside of them is consumed but the secondary batteries are capable of recharging and hence in this article the word of battery refers to this kind.

Fuel cell and batteries consist of two electrodes which are located in an electrolyte, and these elements are packed together in a

**Table 2**
Applications of battery storage systems in stabilizing and improving the operation of power grids.

| Application category | Description |
|---|---|
| Grid angular stability (GAS) | The power oscillation can be mitigated through absorption and injection of real power supplied by the battery. |
| Grid voltage stability (GVS) | Any voltage quality degradation can be compensated through injecting active and reactive power supplied by the battery. |
| Grid frequency excursion suppression (GFS) | Battery can provide the central generation unit with enough real-time spinning reserve or load in order to keep balance between supply and demand. |
| Short duration power quality (SPQ) | Lead–acid batteries can provide the power grid with the capability of mitigating voltage sags during any event such as reclosing. |
| Long duration power quality (LPQ) | The time which is required for SPQ plus several hours supplying reserve power. |

container connecting to an external load or source through positive (cathode) and negative (anode) connectors. The duty of electrodes is to exchange ions with the electrolyte and electron through an external circuit. As shown in Fig. 10, the anode is the electrode which is oxidized sending positive ions to the electrolyte during the discharge process. In this mode, the anode behaves as an electron source for the load. At the same time, cathode receives the electrons from the load passing them to the positive ions inside the electrolyte. To keep the current in the external circuit, electrons should be generated at the anode and consumed at the cathode at the same time [67].

The voltage at the battery terminals is equal to the electromagnetic force (EMF) minus the voltage depression across the battery due to its internal resistance. The batteries are rated according to the amount of power and energy which can supply. Efficiency and lifespan together with operating temperature, depth of discharge (DOD), and energy density, are other characteristics of a typical battery. The lifespan is the period of time in which a battery operate normally (nominal duration of supply) and it is stated in terms of number of cycles, after this time, the battery keeps the energy in shorter period of time. The depth of discharge reflects the level of discharging which a battery is allowed to go to that level [10].

Rechargeable (secondary) batteries are employed in many applications such as lighting, starting, and ignition automotive applications, handling tools for moving materials in industrial trucks, standby and emergency power, portable gadgets such as toys, flashlights, and more electronic devices such as camcorders, computers and hand-phones. Batteries are also used in electric hybrid vehicles (EHV) and large scale utility storage systems. In utility applications batteries are utilized to level the load, adjust the frequency and provide spinning reserve which result in favorable system economics [68].

Battery storage system can bring many benefits where there are distributed energy generation systems with limited prime-movers such as sun and wind. In this case, the exceeded energy produced during the low consumption periods can be stored in the batteries in order to be used during the peak times [62]. The batteries that are utilized in power system applications are those which have a deep cycle characteristic. In these types, the energy capacity is ranged from 17 to 40 MWh bringing a boundary of efficiency about 70–80% [10].

### 3.2.1. *Battery energy storage systems (BESSs)*

Between different types of batteries, those are suitable for power system applications (Table 2) have been discussed in the followings [10,68].

*3.2.1.1. Lead acid batteries.* Lead acid batteries are the most common type of electrochemical storage devices (more than 90% usage in the current market). Two electrodes i.e. lead dioxide positive and lead negative are sealed in a sulfuric acid electrolyte and the whole package is called lead acid battery [26]. This type of battery has two varieties, namely, valve regulated lead acid (VRLA) and flooded or vented lead acid (VLA). In former, the electrolyte is confined in an absorbent material which is called separator and in latter, as illustrated in Figs. 11–13, the electrodes are dunked in a tank of electrolyte. The economic analysis confirms that lead–acid batteries are well-suited for many applications which are listed in Table 2 [26].

The most common battery rating is the ampere hour (A h) rating. This is a unit of measurement for battery capacity obtained by multiplying a current flow in amperes by the time in hours of discharge. Manufacturers use different discharge periods to yield different ampere hour ratings for the same capacity batteries, therefore, the Ah rating has little significance unless qualified by the number of hours which is taken to discharge the battery. For this reason A h ratings are only a general method of evaluating a battery's capacity for selection purposes. As shown in Fig. 14, the nominal capacity of a lead acid battery is a function of its temperature meaning that the higher the temperature, the more the capacity is available.



**Fig. 11.** Typical Flooded lead-acid battery [132].



**Fig. 12.** Typical Valve Regulated Lead-acid battery [132].

*3.2.1.2. Sodium sulfur (NaS).* Ford motor company was the first leader of research in the area of NaS batteries [26,68]. They started their studies in order to investigate the possibility of utilizing Beta-alumina (B-$AL_2O_3$) as the solid electrolyte. The structure of a basic NaS cell is depicted in Fig. 15. The active substance which sets up the negative electrode is the liquid (molten) sodium and B-$AL_2O_3$ which is a ceramic material makes the electrolyte. The battery cell is a tall cylindrical structure that is contained by a fixed metallic cover sealing from its top side. The cells in bigger sizes are more

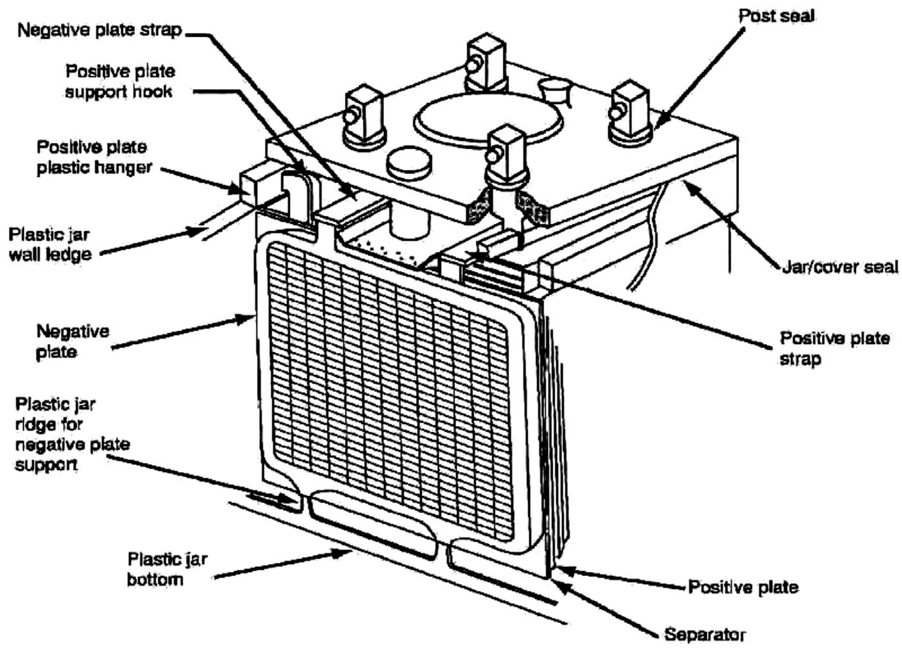



**Fig. 13.** Cross-sectional view of a flooded lead-acid battery [26].

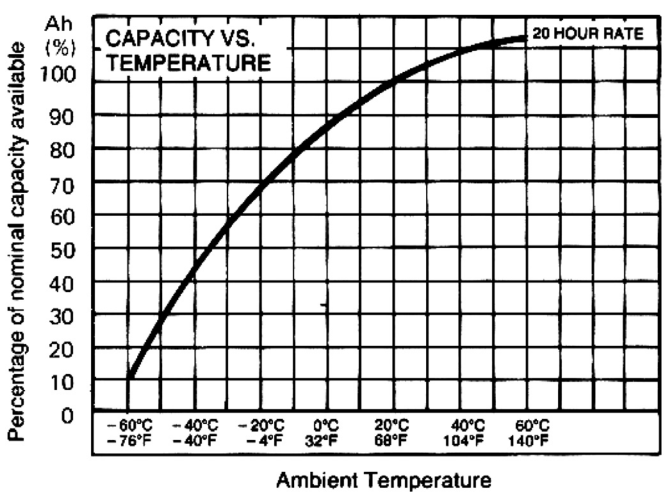



**Fig. 14.** Impact of temperature on capacity for lead-acid batteries [132].

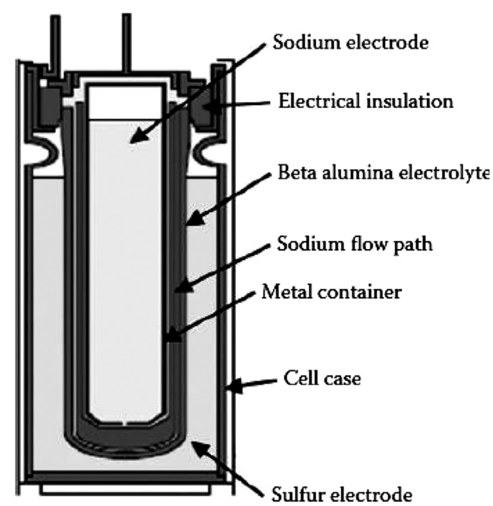



**Fig. 15.** Physical structure of NaS battery including main parts [68].

economically feasible in comparison with the smaller ones. This matter is practically useable in commercial buildings where the heat conservation is important [68].

Sodium sulfur batteries are capable of operating in a temperature ranging from 300 to 350 °C. In this range the conductivity of ceramic material is very remarkable so that in 350 °C the resistivity of battery is about 4 Ω cm [53]. The amount of heat required for the discharge and charge reactions is adequately supplied by the reactions themselves and hence there is no need to have an external source to generate the heat. As shown in Figs. 16 and 17, sodium is propagated from the negative electrode and after passing through the Beta-alumina cylinder, it reacts with the liquid solution. The capacity of a NaS battery is normally identified by the range of composition of this sodium sulfur liquid. The voltage produced by an individual cell is over 2 V [53].

The application of Sodium sulfur batteries is normally limited in two groups, namely, stationary and motive. For the former, the application utility power grids such as load leveling, peak shavings, and power quality can be proper examples. For the latter, motive applications consist of electrification of motive devices such as electric cars, buses, and hybrid buses and trucks can be suitable samples. The utilization of NaS storage batteries has its own limitations and advantages and these points are cited in Table 3 [68]. To utilize the NaS battery storage system utilities, “F” category (SPQ) is the best suited ones [26].

*3.2.1.3. Lithium ion (Li-ion).* In the early 1990s, the lithium ion (Li-ion) battery was introduced to the world. Before this period, the only solution for the portable electronic devices was nickel–metal hybrid batteries. In comparison with the nickel–metal hybrid batteries, the Li-ion batteries are lighter providing more capacity and power. A Li-ion battery is composed of three sheet layers i.e. a positive electrode, a negative electrode and a separator

[62]. The first sheet is made of lithium cobalt oxide ($LiCoO_2$) and the second one is generally graphite ($C_6$) and the last one is the electrolyte. The electrolyte is made up of lithium salt ($LiPF_6$) which is dissolved in organic carbonates [69].

During the discharging reaction, the positive lithium ions move toward cathode ($LiCoO_2$). When a positive ion reaches to the cathode at a same time an electron moves from the negative sheet to positive sheet through an external circuit (Fig. 18). When the Li ions detach and move to the opposite sheet, an electron will be detached as well because Li ions are positively charged. This electron will flow out of the battery through the external circuit and then back into the opposite side to recombine with the Li-ion. In the charging reaction, the electrons from the external power source are combined with lithium ions generated by the cathode

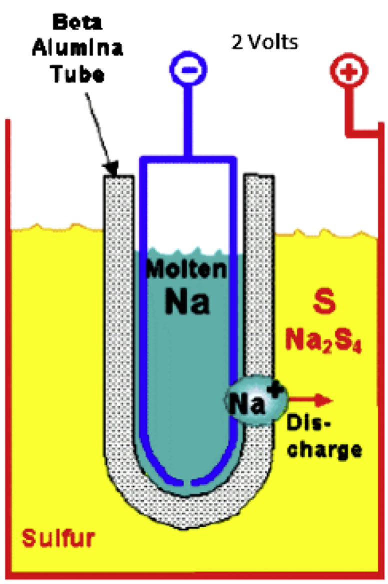



**Fig. 16.** Sodium–sulfur (NaS) batteries use molten sodium and sulfur separated by a ceramic electrolyte [132].

and move towards the anode through the electrolyte. The migrated lithium ions from the cathode are deposited between the carbon layers in the shape of lithium atoms once they reach to the anode. Lithium ion batteries have some drawbacks such as [68]

- High cost.
- Complex protective circuitry.
- Overcharging.
- Overheating which results in decreasing the performance of battery i.e. thermal runaway, loss in capacity and undesirable side reactions.

*3.2.1.4. Flow batteries.* A redox flow battery is a type of secondary rechargeable battery and in this type the energy is stored chemically in liquid electrolytes (sulfuric acid) containing different redox couples with electrochemical potentials sufficiently separated from each other. These electrochemical materials produce electromotive (EMF) force to run the oxidization–reduction reactions required to charge and discharge a redox cell. There is also a separate storage tank which is responsible for pumping the electrolyte into flow cells across a proton exchange membrane. As depicted on Fig. 19, one of electrolytes is supposed to be electrochemically oxidized and another one reduced [68].

Before emerging the vanadium redox flow batteries (VRFBs), the main disadvantage to flow batteries was that the two electrolytes were made of dissimilar materials separated by a thin membrane. After sometime these two substances would mix together and make the battery useless. The main advantage of VRFBs is that vanadium is utilized in order to form both negative and positive electrodes while they are operating in different oxidization states. Four oxidization states are presented for vanadium i.e. $V^{+2}$, $V^{+3}$, $V^{+4}$, and $V^{+5}$. The solution is the place in which the electrode reactions are taken place. The reaction at the negative electrode, in discharge state, is $V^{2+} \rightarrow V^{3+} + e$ and the reaction at the positive electrode is $V^{5+} + e \rightarrow V^{4+}$. The mentioned reactions are both reversible on the carbonized electrode [68].

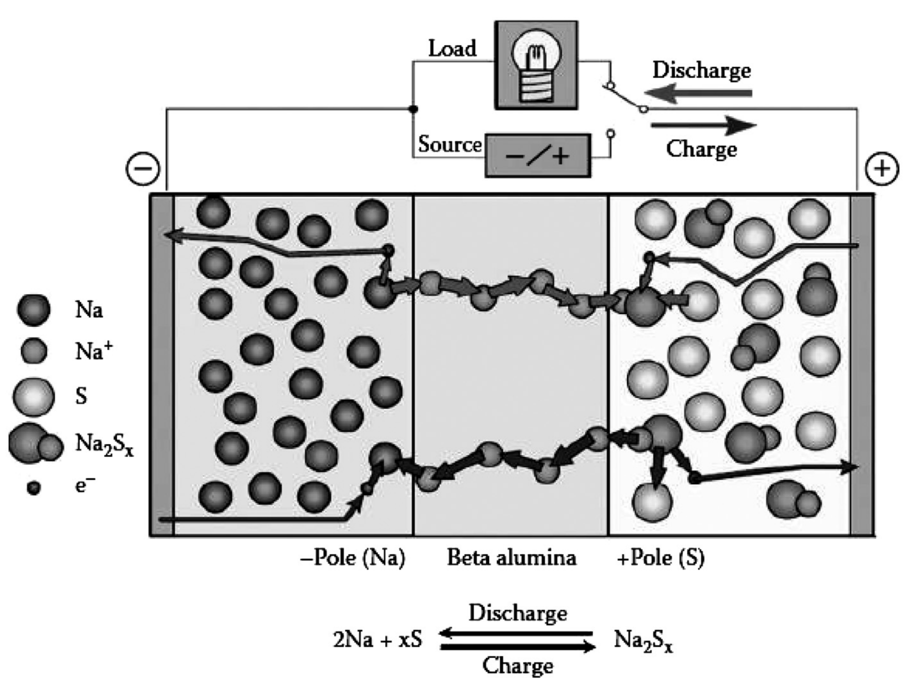



**Fig. 17.** Electron and ion motion during discharge and charge cycles [68].

**Table 3**
Properties and primary limitations of sodium–sulfur system [68].

| Characteristic | Comments |
|---|---|
| Advantages | |
| Potential low cost relative to other advanced batteries; high cycle life; high energy; good power density; flexible operation; high energy efficiency; insensitivity to ambient conditions; state-of-charge identification | Inexpensive raw materials, sealed, no-maintenance configuration; liquid electrodes; low-density active materials; high cell voltage; cells functional over wide range of conditions (rate, depth of discharge, temperature); >80% due to 100% Coulombic efficiency; reasonable resistance; sealed high-temperature systems; high resistance at top of charge; straightforward current integration due to 100% Coulombic operation. |
| Limitations | |
| Thermal management; safety; seal and freeze–thaw durabilities | Effective enclosure required to maintain energy efficiency and provide adequate stand time; reaction with molten active materials must be controlled; cell hermeticity required in corrosive environment due to use of ceramic electrolyte with limited fracture toughness that can be subjected to high levels of thermally driven mechanical stress. |

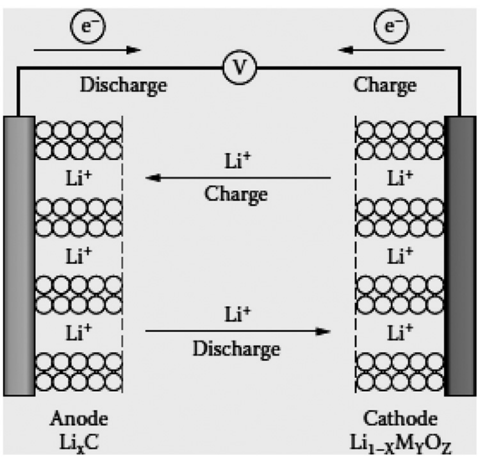



**Fig. 18.** Charge and discharge cycles of typical lithium ion battery [68].

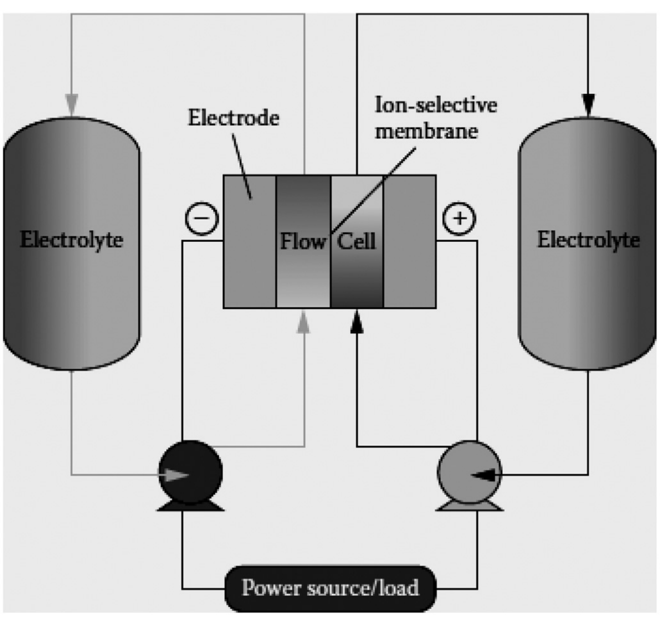



**Fig. 19.** Flow battery that stores energy in liquid electrolytes [68].

To separate the electrolytes an ion-selective membrane is utilized which makes two compartments to exchange negative and positive ions. The electrolyte can be used unlimitedly since it is returned to the same state at the end of each cycle. The negative half-cell uses ($V^{2+}$, $V^{3+}$) redox couple while the positive half-cycle uses the ($V^{2+}$, $V^{3+}$) redox couple. Although $V^{2+}$, $V^{3+}$, and $V^{4+}$ types are very soluble in sulfuric acid, the stability of $V^{5+}$ for long-term usage is rather restricted due to the generation of insoluble $V_2O_5$ which deposits at high temperatures [68].

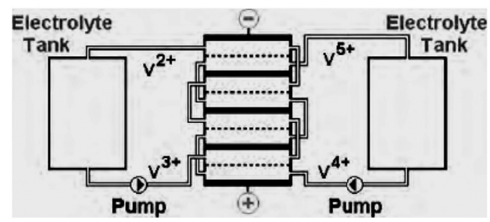



**Fig. 20.** Cellenium Series Flow Design [26].

**Table 4**
Various redox systems used in flow batteries [53].

| System | Negative electrode reactant | Positive electrode reactant | Nominal voltage (V) |
|---|---|---|---|
| V/Br | V | Bromine | 1.0 |
| Cr/Fe | Cr | Fe | 1.03 |
| V/V | V | V | 1.3 |
| Sulfide/Br | Polysulfide | Bromine | 1.54 |
| $Zn/Br_2$ | Zn | Bromine | 1.75 |
| Ce/Zn | Zn | Ce | $<2$ |

The reaction cells together with their electrodes are grounded in group constructing blocks and a series combination of blocks is known as stacks (Fig. 20). The stack structure is set up by two plates connected to the positive and negative electrodes from both sides of stack. In VRFB the cells share the same electrolyte and this feature makes the VRFBs different from the conventional batteries in which the operation of whole battery was affected by one cell in the string [68]. Some of the redox systems that have been explored are mentioned in Table 4.

The standard cell potential is 1.26 V but under actual operating conditions, the open circuit voltage (OCV) is as high as 1.4 V at 50% state of charge (SOC) and 1.6 V at 100% SOC. As shown in Fig. 21, along with the increae of the SOC, OCV also increases. The OCV across the electrolyte is determined by the difference in the chemical potentials on its both sides. As current passes through the cell protons are transferred, changing the pH, so that the ionic compositions of the two electrode reactant fluids gradually change. Thus, the cell potential varies as SOC varies and the change in the voltage with the amount of charge passed through depends on the size of the tanks.

The system storage and power capacity are independent because solutions are utilized in the structure of a VRFB. This feature of VRFBs makes them scalable to a wide range of current,

voltage, and capacities for different applications. The higher the power generation needs only to increase the size of electrolyte storage tanks. Although the system theoretically can supply unlimited amount of energy, in practice, the $V_2O_5$ limits the energy density of a VRBF to about 167 Wh $kg^{-1}$. A comparison between energy density for other types of storage system is depicted on Fig. 22. For instance, a 600 MWh vanadium redox flow battery system requires 30 million liters of electrolyte which can occupy a football field if storage tanks are used. A well-structured vanadium redox cell should satisfy bellow requirements

- Oxygen accessibility to the negative electrolyte chamber must be avoided.
- The bipolar plates must be connected to the electrodes properly. Appropriate connection of current collectors also must be considered since the activation layer are thermally connected to them.
- Charging value must be limited to maximum of 1.7 V to prevent damage to the carbonic current collectors.
- Electrolytes must be selected from the materials with high conductivity and wettability.

*3.2.1.5. Metal air.* Metal–air batteries are the most compact and, potentially, the least expensive batteries available. They are also environmentally benign. The difficulty and deficiency to recharge can be the only disadvantage of this type. Since many manufacturers offer refuelable units, where the consumed metal is mechanically replaced and processed separately, not many developers offer electrically rechargeable batteries. The life cycle of rechargeable metal air batteries that are under development is only a few hundred cycles and their efficiency is about 50%.

The anodes in this type are generally made of metals with high tendency of oxidization and releasing electrons such as zinc or aluminum. The cathodes or air electrodes are often constructed from a porous carbon structure or a metal mesh covered with proper catalysts. The electrolytes are often a good $OH^-$ ion conductor such as KOH. The electrolyte may be in liquid form or a solid polymer membrane saturated with KOH. While the high energy density and low cost of metal–air batteries may make them ideal for many primary battery applications, the ability to recharge such batteries needs to be improved before they can compete with other types of rechargeable battery technologies. Fig. 23 shows the charge and discharge processes for a typical metal air battery in which the zinc is used as the anode and oxygen is used as the cathode [70].

*3.2.1.6. Battery energy storage systems (BESSs) applications.* Large-scale electrical energy storage systems are essentially needed to support an electricity grid and operating electrical vehicle as the fraction of renewable energy generation from sources such as solar and wind energy increases. In this section attempt has been made of emphasize the various battery storage technology in actual use.

Nair and Garimella [71] have assessed the battery energy storage systems for small scale renewable energy integration. It was found that high initial investment is the main hindrance to use of nickel–cadmium (NiCd) batteries in renewable energy applications and its performance is at par with nickel–metal hydride (NiMH) batteries. There are two major factors which allow its dominating use of lead acid batteries in renewable energy systems i.e. affordability and availability.

A comparison between batteries and generators, as power sources for use with mobile robotics, was carried out by Logan et al. [72]. The useful design tool, when sizing power systems, was drawn from the study and shown in Fig. 24. It reveals that zero reserve fuel line intersection occurs at the point where generators become more efficient than batteries from a specific energy point of view. Points on the zero reserve fuel line represent the power output of a generator and battery system with a mass equal to that of a battery containing the same amount of energy as is available from the generator. The 300% and 600% reserve fuel lines are similar except the system consists of the generator, additional fuel, and a battery. The 300% reserve line represents enough additional

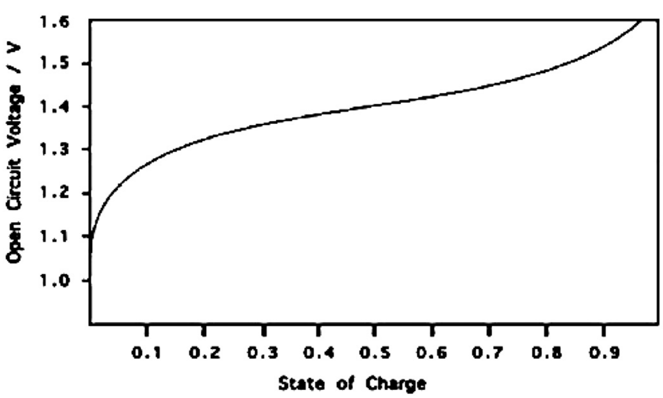



**Fig. 21.** Variation of the open circuit voltage versus state of charge for the case of a V/V cell at 298 K [53].

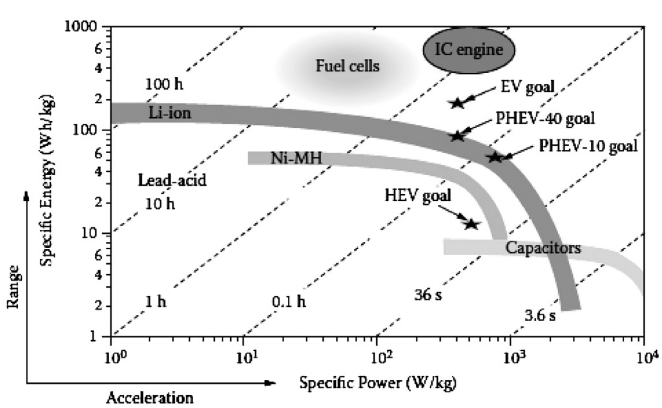



**Fig. 22.** Plot of energy versus power for various energy systems [68].

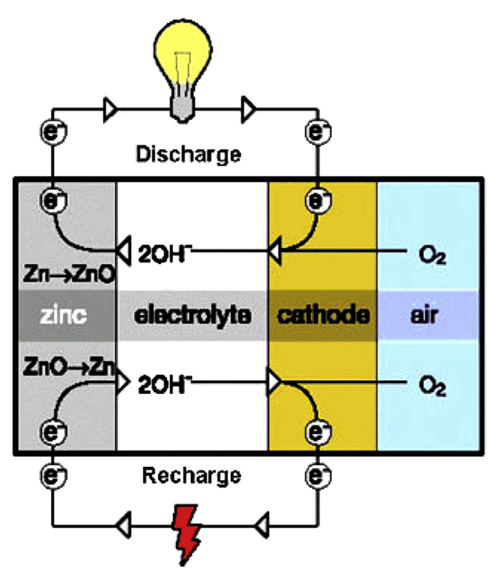



**Fig. 23.** charge and discharge processes for a typical metal air battery [70].

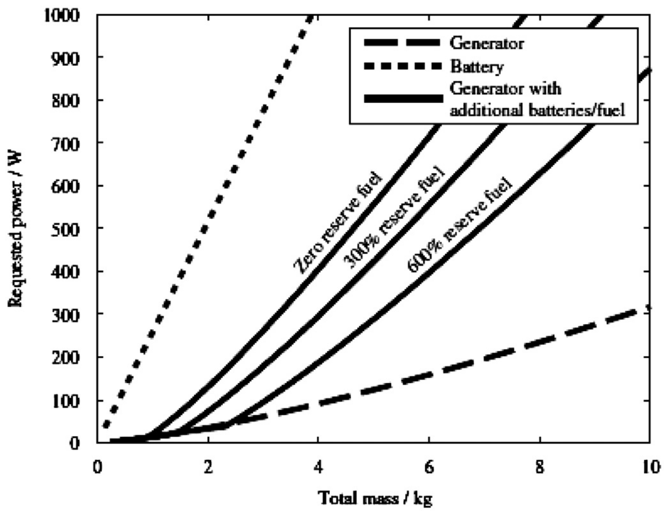



**Fig. 24.** Comparison of peak power output of battery and generator.

**Table 5**
Battery status after discharge.

| Load (kW) | Discharge time | Cell, $V_{max}$ (V) | Cell, $V_{min}$ (V) | SOC (%) | Cell, $T_{max}$ (°C) | Stopped by alarm |
|---|---|---|---|---|---|---|
| 50 | 14 min 34 s | 3.12 | 2.48 | 3 | 32 | Low cell, $V_{min}$ |
| 75 | 10 min 30 s | 3.13 | 2.48 | 3 | 51 | Low cell, $V_{min}$ |
| 100 | 3 min 40 s | 3.38 | 3.35 | 71 | 55 | Over temperature (55 °C) |

fuel to provide four times the energy of an equivalent mass battery, and the 600% reserve line represents enough fuel to provide seven times the energy of an equivalent mass battery.

Clark and Doughty [73] developed and tested of 100 kW/min Li-ion battery systems for energy storage applications. During battery testing, the system's Li-ion battery was used as the dc source rather than a rectifier. The critical load was simulated by connecting the power conditioning system (PCS) output to a three-phase resistive load at three power levels (50, 75, and 100 kW) and battery's charge and discharge functions were tested for each unit. The test results of the batteries are cited in Table 5.

The battery–capacitor combinations features were introduced by Kan et al. [74]. They examined the Li-ion batteries for experimental investigation as illustrated in Fig. 25. They found that indeed the capacity of Li-ion batteries decreases in each cycle. This decrease is even larger if the battery is not fully charged in each cycle. They found a degradation of about 2% in 37 cycles.

Appleby [75] studied the application of lead/acid batteries as energy storage and its utilization in transportation sector. During the testing, the electrical vehicle worked satisfactory with polymer-exchange-membrane (PEM) fuel cell. They found the same recharging logistics as those of a gasoline vehicle with much improved energy efficiency. During the study it was also found that a loading of 0.15 g/kW appears feasible and hence the major production of such vehicles will allow platinum producers to keep pace. The advent of the PEM-fuel-cell/battery hybrid vehicle will open up a larger market for rechargeable batteries than that for vehicles which use traction batteries alone.

The lithium-ion batteries for electric power storage with specific cell having high energy density and long life were developed by Haruna et al. [76]. The compression in electrodic material and energy density are given in Table 6. The cell chemistry consisted of a positive electrode containing a lithium–manganese spinel or a mixture of it with a layered-manganese-based material, and a negative electrode containing a hard carbon.

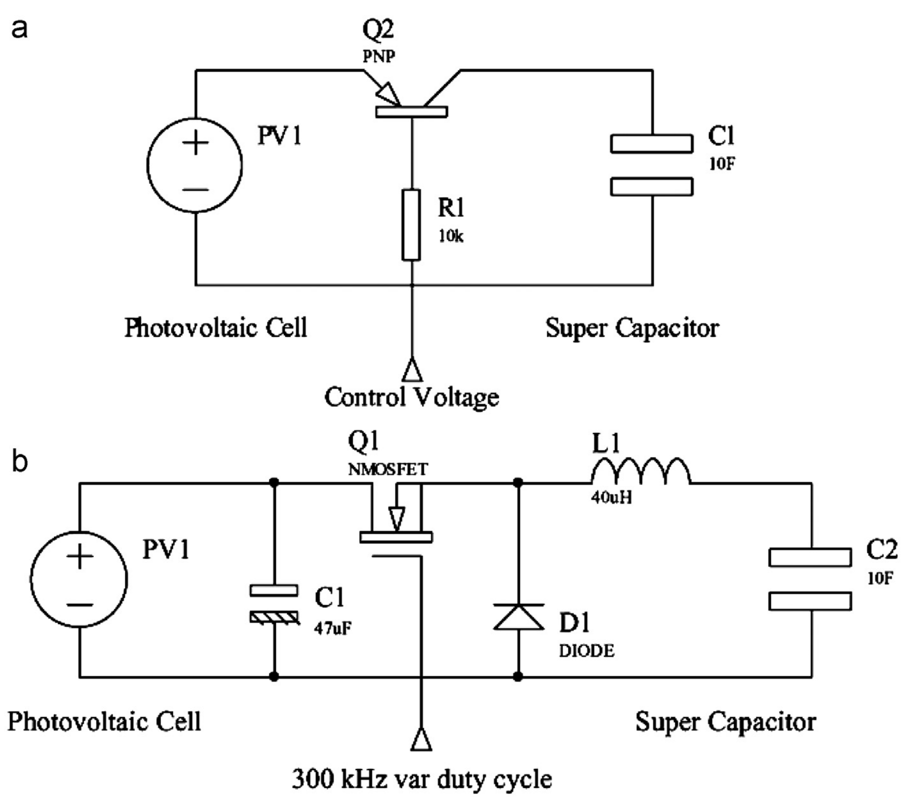



**Fig. 25.** (a) Direct charging of capacitor (linear) and (b) charging of capacitor via inductance (switching).

The 8 A h-class cells consisting of these cell chemistries showed that their extrapolated lives were long enough to withstand a cycling load for 10 years of use. They also manufactured two types of 100 A h-class cells as an experiment based on the results for the 8 Ah-class cells. They showed specific energies of 100 Wh $kg^{-1}$ and 106 Wh $kg^{-1}$.

Chang et al. [77] emphasized the utilization of lead–acid batteries in PV/wind power systems. They found that lead-acid batteries, especially the floating valve regulated lead acid (VRLA) design or the improved one based on VRLA, and the open flooded types, have a dominant advantage in PV/wind power generation systems at present by virtue of their particular technology and cost advantages. The advantages and disadvantages of traditional open batteries and sealed VRLA batteries are presented in Table 7.

Padbury and Zhang [78] work was focused for recent development and application hurdle of lithium–oxygen batteries in actual use. There is no doubt that it received attention due to their extremely high theoretical energy densities which far exceed that of any other existing energy storage technology. The significantly larger theoretical energy density of the lithium–oxygen batteries is due to the use of a pure lithium metal anode and the fact that the cathode oxidant or oxygen is stored externally since it can be readily obtained from the surrounding air. The lithium–oxygen battery consists of a porous carbon cathode designed to promote oxygen diffusion and reduction and a pure lithium metal anode as shown in Fig. 26. The two electrodes are separated by a lithium-ion conducting electrolyte. They mainly focus on possible areas for future research include the development of anodes that are stable or protected from moisturized, cathode structures that have improved and optimized mesoporosity for facilitating high oxygen diffusivity while maintaining high electrical conductivity, electrolytes that have high oxygen solubility and diffusivity along with good lithium-ion conductivity.

The development of hydrophobic electrolytes is also important for the development of the lithium–air battery catalysts that facilitate the oxygen evolution reaction and reduce the over potentials on charging and discharging. Short and long duration performance was evaluated on batteries operated electric vehicles by Gerssen-Gondelach and Faaij [79]. They selected five different battery technologies for assessment purpose. The schematic view of energy flow from battery to wheel is illustrated in Fig. 27. They reported that wheel-to-wheel energy consumption and emissions of battery electric vehicles (BEVs) are lowest for lithium-ion batteries; 314–374 Wh/km and 76–90 $gCO_2eq\ km^{-1}$ (assuming 593 $gCO_2$ kW/h for European electricity mix), compared to 450–760 Wh/km and 150–170 $gCO_2eq\ km^{-1}$ for petrol and diesel cars. The total driving costs are lowest for ZEBRA batteries (0.43–0.62 $/km). However, only if ZEBRA batteries attain a very low cost of 100 $/kWh and driving ranges are below 200 km, BEVs become cost competitive compared to diesel cars.

Chakrabarti et al. [80] assess the performance of a standalone redox flow battery system for solar energy storage with undivided reactor configuration deployed along with porous graphite felt electrodes and ruthenium acetylacetonate as electrolyte in acetonitrile solvent (as illustrated in Fig. 28). They reported that an optimum power output of 35 mW was obtained upon discharge at 2.1 mA/$cm^2$. As the concentration of ruthenium species increases starting from 0.02 M to 0.1 M, the current densities and power output are getting higher by a factor of five. Voltage efficiencies are higher at concentrations of 0.1 M ruthenium acetylacetonate (55% when battery is full of electrolytes and 48% when empty) which confirms that the all-ruthenium redox flow battery has some promise for future applications in solar energy storage.

Narayanan et al. [81] also reported that the iron-air rechargeable battery has the potential of meeting the requirements of grid-scale energy storage. They found that this battery technology can be transformational because of the extremely low cost of iron, the extraordinary environmental friendliness of iron and air, and the abundance of raw materials. The key technical challenges that

**Table 6**
Specification of 8 A h-class cells.

| | Electrode materials | | Energy density (Wh $kg^{-1}$) |
|---|---|---|---|
| | Positive | Negative | |
| Cell A | Li–Mn-spinel | Hard C | 80 |
| Cell B | Li–Mn-spinel/layered | Hard C | 100 |
| Cell C | Li–Mn-spinel/layered | Natural graphite | 130 |

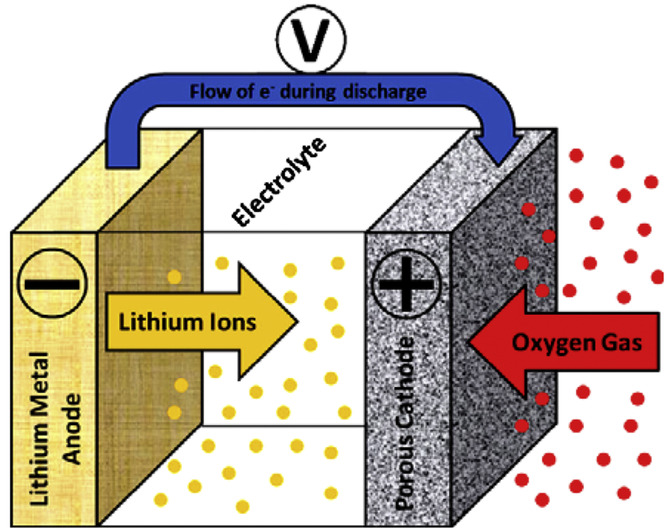



**Fig. 26.** Schematic diagram of a lithium–oxygen battery showing reduction of oxygen at the porous cathode and oxidation of lithium metal at the anode.

**Table 7**
Comparison of open flooded and floating VRLA batteries.

| Floating-charge VRLA batteries | | Floating-charge VRLA batteries | |
|---|---|---|---|
| Advantages | Disadvantages | Advantages | Disadvantages |
| Non-flowing electrolyte<br>Sealed<br>No liquid leakage, acid fumes, or equipment corrosion<br>Unnecessary to add water or acid<br>Flexible installation<br>Small footprint<br>Low self discharge<br>PbCaSn alloy meet the environmental requirement | High/low temperature properties<br>Short deep cycle life | Long cycle life | Flowing electrolyte<br>Not Sealed<br>Acid fumes during charge/discharge; equipment corrosion<br>Frequent need to add acid and water<br>Vertical installation only<br>Large footprint<br>High self discharge<br>PbSb alloy pollutes environment |

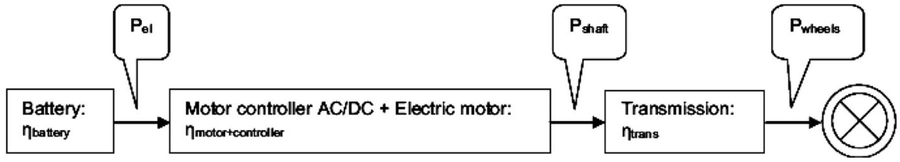



**Fig. 27.** Main element and power flow inside a battery electric vehicle.

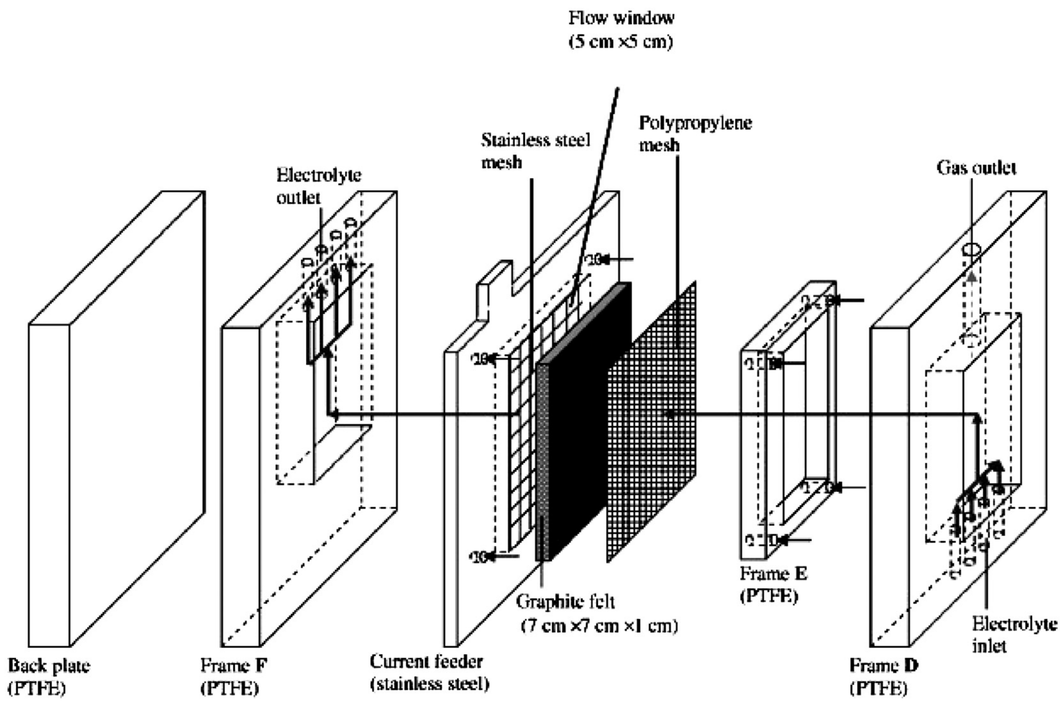



**Fig. 28.** Half-cell stack components of the undivided redox flow battery. Small arrows indicate where plastic bolts and nuts were fitted.

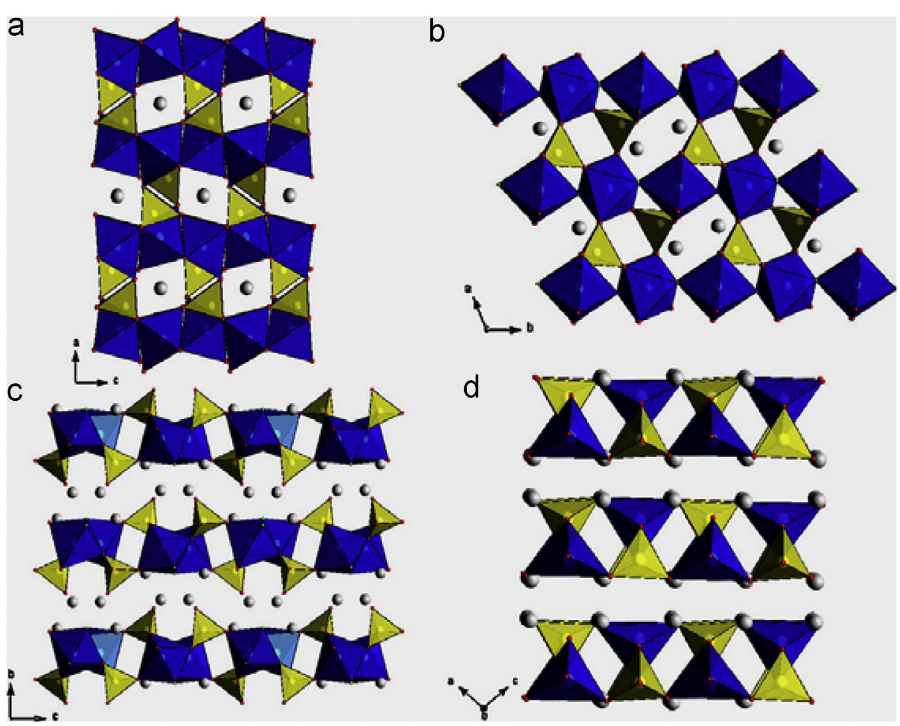



**Fig. 29.** Graphical representation of key polyanionic structures for lithium-ion batteries.

hinder the successful commercialization of the iron–air battery are its efficiency and cycle life.

New composite materials for lithium-ion batteries has been studied by Ellis et al. [82] and reported that nanostructured electrode compounds has opened up the field of polyanionic materials and Si-based composites as positive and negative electrode materials, respectively. The structures of these compounds are shown in Fig. 29. This is promising new materials with high capacity and high potential have driven interest in this field.

### 3.2.2. Regenerative fuel cell (RFC)

Regenerative or reversible fuel cells (RFC) are electrochemical systems that transform chemical energy to electrical energy (fuel cell mode) and decompose the water molecule into hydrogen and oxygen in reverse reaction (electrolyzer mode). The reactions which are taken place in electrochemical cells are called reduction–oxidation (redox) reactions. The full reaction is divided in two half-cell reactions or half-reactions which occur in physically separate regions of device. These areas are chemically interconnected through a solution which is called electrolyte and it conducts ions but not electrons. Like as conventional batteries, there is a need for an external circuit to transfer the electron from the oxidizing half-reaction side to reduction side establishing a flow of electrical current. The current exits the device from the reduction side which becomes the cathode (positive electrode) of the cell, and enters the device at the oxidizing side which becomes the anode (negative electrode) [54].

To explain how a fuel cell operates (Fig. 30), let us consider a membrane which can act as an electrolyte. It is supposed to put hydrogen in contact with one side of this membrane. At ambient conditions, most of the hydrogen gas will be in the form of $H_2$ molecules but there is still a small amount of gas which is dissociated according to Eq. (4).

$$H_2 \rightarrow 2H \tag{4}$$

and some of the resulting H will oxidize (ionize) losing an electron based on Eq. (5).

$$H \rightarrow H^+ + e^- \tag{5}$$

The membrane is not able to conduct electrons and hence electrons remain on its surface while the hydrogen positive ions diffuse across it reaching to other side. By increasing the number of positive ions at the reduction side, an electrical field is formed. The electrical field causes the electrons flow from the hydrogen side to other side (oxygen) through the external circuit as indicated in Fig. 31.

The half-reaction at the anode and cathode sides can be equated as Eqs. (6) and (7), respectively.

$$2H_2 \rightarrow 4H^+ + 4e^- \tag{6}$$

$$4e^- + 4H^+ + O_2 \rightarrow 2H_2O \tag{7}$$

The cathode reaction is high exothermal releasing energy that powers the fuel cell. The amount of hydrogen dissociation can be increased by changing the environmental variables such as temperature. Fuel cells can be classified as cited in Table 8. Fig. 32 gives a good understanding about the physical structure of a regenerative fuel cell together with its chemical reactions.

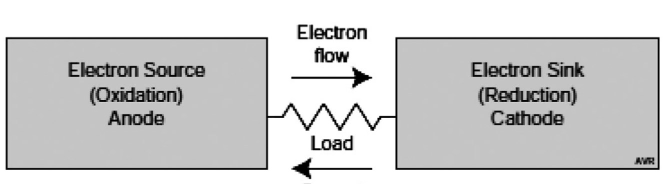



**Fig. 30.** An electrochemical cell must consist of a source and sink of electrons [54].

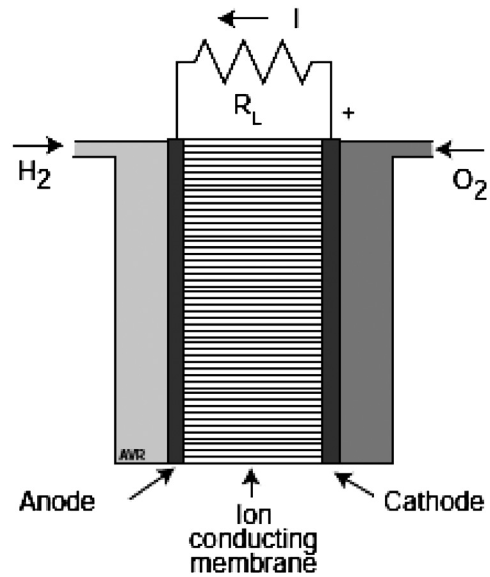



**Fig. 31.** Simplest electrochemical cell [54].

**Table 8**
Various types of fuel cell [54].

| | |
|---|---|
| AFC | Alkaline fuel cell |
| DMFC | Direct methanol fuel cell |
| MCFC | Molten Carbonate fuel cell |
| PAFC | Phosphoric acid fuel cell |
| SAFC | Solid acid fuel cell |
| SOFC | Solid oxide fuel cell (ceramic) |
| SPFC | Solid polymer fuel cell |

Fuel cell energy conversion devices and use of hydrogen as an energy carrier have benefited from major technological advancements in recent years. The fuel cell technology has also received considerable attention as an alternative to the conventional power units due to its higher efficiency, clean operation and cost-effective supply of power demanded by the consumers [83]. Fuel cells can also provide continuous power with extremely low (or zero) criteria pollutant and greenhouse gas emissions from a variety of renewable and fossil fuels that well compliments the relative intermittency of renewable energy sources [84]. Alkaline fuel cell (AFC), proton exchange membrane fuel cell (PEM), direct methanol fuel cell (DMFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC) technologies were developed in the past decade. Fuel cell can be operated together with a fuel generation device, which is commonly an electrolyzer, to create a regenerative fuel cell (RFC) system. RFC is capable to convert electrical energy to a storable fuel and then use this fuel in a fuel cell reaction to provide electricity when needed [85].

As cited in Table 9, utilization of RFCs is more advantageous than batteries. RFC systems can be used as back-up or standby for power systems and provide a higher degree of utility and reliability than conventional battery sets by providing longer periods of back-up power with less installation impact at lower overall cost [85].

*3.2.2.1. Fuel cell storage system applications.* Integrated fuel cells type, primary and secondary batteries, attracted a great deal due to their high theoretical power densities. A novel integrated FC type accumulator based on nonprecious-metals was developed by Bretthauer et al. [86]. The main component of the developed accumulator was its alkaline polymer electrolyte membrane that allows not only the usage of a low cost $AB_5$ type hydrogen storage

electrode, but also the usage of $La_{0.6}Ca_{0.4}CoO_3$ as a precious-metal free bi-functional catalyst for the air-breathing electrode. They also optimized the catalyst ink and spray coating technique in order to improve the polarization of the air-breathing electrode and minimize overvoltage losses. The solid oxide electrolysis cells (SOEC) have attracted a great interest in the last few years, as they offer significant power and higher efficiencies compared to conventional low temperature electrolyzer [87]. A typical fuel cell consists of an electrolyte in contact with anode and cathode is depicted in Fig. 33 [88].

Faro et al. [89] investigated a new catalyst formulation characterized by mixed electronic–ionic conductivity for solid oxide fuel cells (SOFCs). They suggested that in the presence of ionic oxygen ($O^{2-}$) dry methanol can be directly oxidized to $CO_2$ at the SOFC anode. Power densities of about 350 mW/cm$^2$ were achieved with an electrolyte supported SOFC using both syngas and pure (dry) methanol. No significant carbon formation for direct oxidation of dry methanol in SOFCs was observed for this catalyst.

The national fuel cell research center (NFCRC) is conducting research on advance understanding of high efficiency, zero emissions coal-based power plants that use hybrid fuel cell-gas turbine technology. This future technology can provide a pure $CO_2$ stream for sequestration, and co-produce hydrogen and electricity (from an SOFC, gas turbine and steam turbine) with a mixed overall efficiency of 65%. These systems would also have nearly zero emissions of criteria pollutants making them a very attractive option for future use of coal in a more sustainable manner [84].

Corbo et al. [90] deal with the application of Li-ion polymer batteries as electric energy storage systems for hydrogen fuel cell power trains. This study showed that the usage of lithium ion polymer batteries permitted to follow the high dynamic requirement of this cycle in hard hybrid configuration, with a hydrogen consumption reduction of about 6% with respect to the same power train equipped with lead acid batteries. Talpone et al. [91] design and assessment of hybrid power generation system based on fuel cells. The system consists of two generation modules and a storage module. The main one is based on a PEM fuel cell stack. The second one, implemented with a programmable electronic source, allows emulating an alternative energy module, particularly a wind energy generation system. The result of this study showed the good agreement with the experimental and theoretical model.

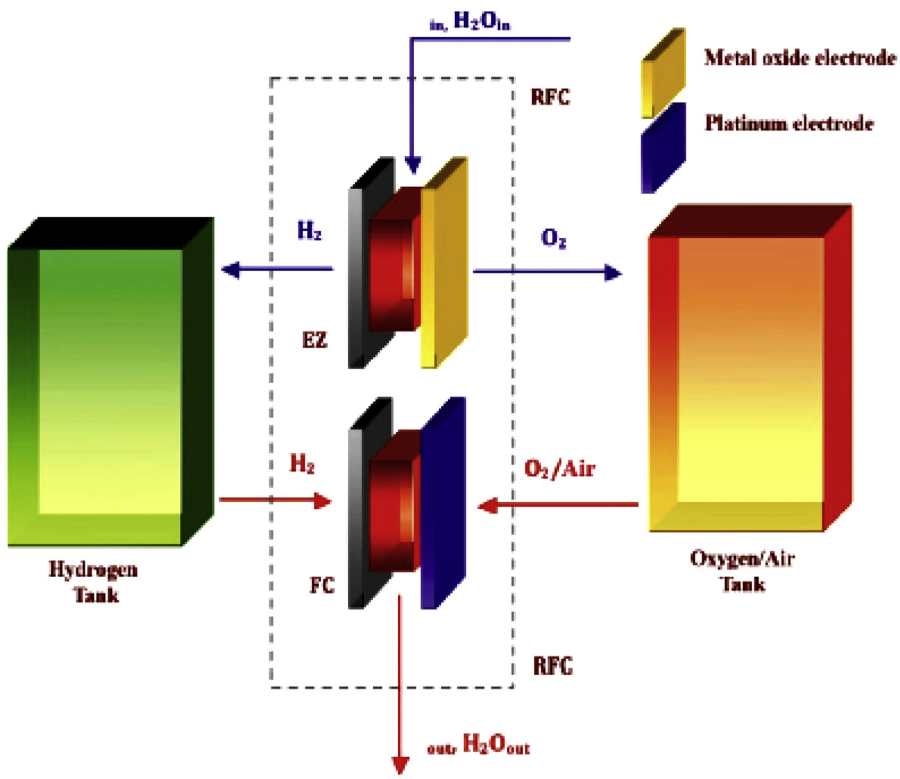



**Fig. 32.** Regenerative fuel cell (RFC) outline [133].

**Table 9**
RFCs show significant advantage over batteries for many applications [85].

| | Batteries | URFC |
|---|---|---|
| Life cost 200 kWh system | US$ 120,000 | US$ 20,000 |
| Incremental additional storage life cycle cost | US$ 150–300/kWh | US$ 20/kWh |
| Calendar life | 6400 at 10% DoD | 20,000+cycles at 100% DoD |
| Maintenance required | Complete battery replacement after cycle life or calendar life limit reached | Cell stack only refurb after 60,000 h |
| Environmental operating hazard | Batteries need indoor storage, acid present | $H_2$ stored outside can be either indoor or outdoor |
| Disposal hazard | Lead, acid issues | None: discharged system has no hazardous materials |

The comprehensive overview of recent developments in SOFC was carried by Huang et al. [92]. The principles of SOFC are discussed in Fig. 34. They also discuss about the core components of SOFC along with their governing equations. The dynamic modeling was illustrated from perspective of power generation to energy losses. The model validation problem and other related challenging issues from the modeling perspective were also pointed out in this paper. The investigation of the direct methanol oxidation in SOFCs was conducted by Faro et al. [89]. They developed a composite Ni-modified $La_{0.6}Sr_{0.4}Fe_{0.8}$–$Co_{0.2}O_3$–$Ce_{0.9}Gd_{0.1}O_2$ electro-catalyst by incipient wetness and subsequent ball milling. They achieved for the direct utilization of methanol (350 mW/cm$^2$) appears promising for SOFC application in remote and microdistributed energy generation as well as for portable power sources.

1D dynamic model for SOFC was developed by Qi et al. [88]. They proposed an approximate analytical solution to deal with the distributed dynamic reacting gas flow problem. By this method, the 1D dynamic SOFC model was simplified to an ODE model as a function of the space, expressed in the form of nonlinear state-space model. This model is useful for designing the distributed parameter control. In this model, the space coordinate is equivalent to a model parameter. This means that the user can determine dynamic responses at any location in the cell by simply substituting the space coordinate into the model to get a state space model. This approach provides an alternative for distributed parameter control of SOFC, such as control of the temperature profile, control of the location of hot spot, etc.

Sommer et al. [93] also studied a dynamic model on the basis of physical properties of the materials, and operating and design

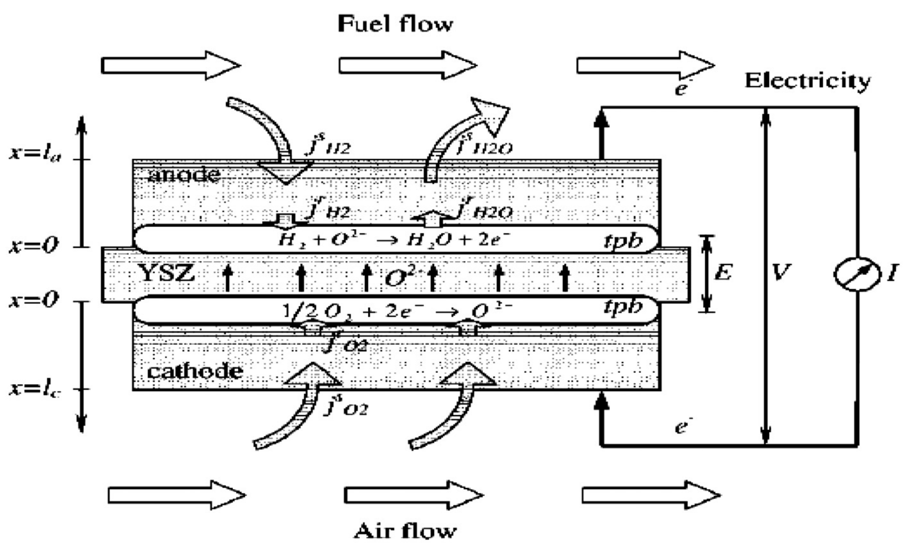



**Fig. 33.** Illustration of SOFC mechanism [88].

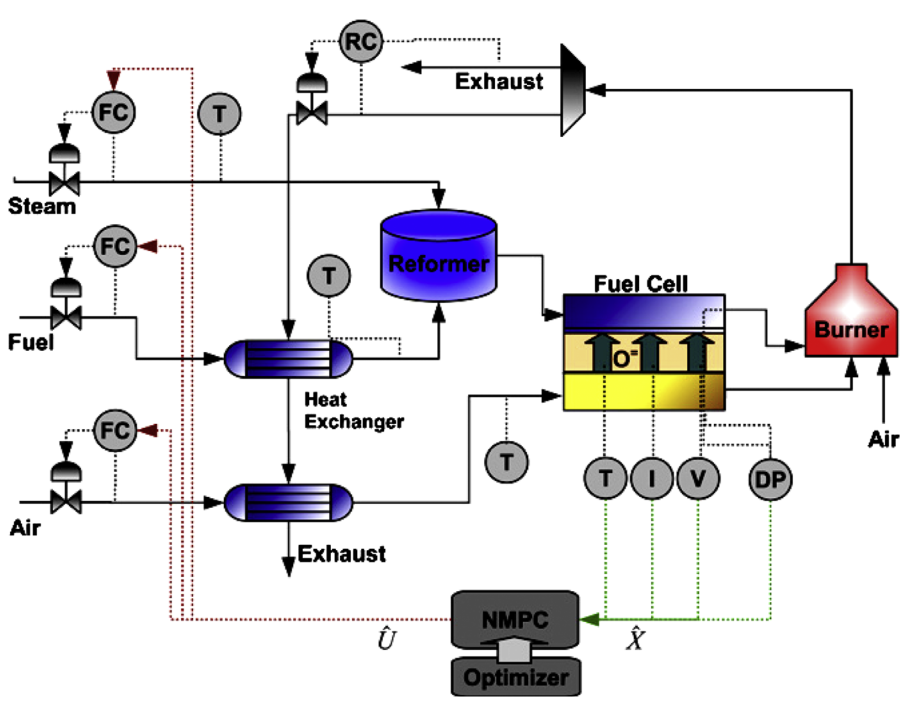



**Fig. 34.** Overview of a SOFC system.

parameters that are computationally fast to predict the response of the single alkaline membrane fuel cell (AMFC). The base of model was electrochemical principles, and mass, momentum, energy and species conservation. It also takes into account pressure drop in the gas channels and the temperature gradient with respect to space in the flow direction. The result of the model was also experimentally validated by direct comparison to voltage and current measurements performed in a cellulose-based AMFC prototype for different electrolyte (KOH) solution concentrations ($y$), showing good quantitative and qualitative agreement. They concluded that the startup transient is short and that there are optimal values of $y$ (40 wt%) which lead to maximum power, that are here in shown experimentally for the first time. Therefore, the adjusted and validated model is expected to be a useful tool for AMFC control, design and optimization purposes.

A one-dimensional, steady-state, two-phase direct methanol fuel cell (DMFC) model was also developed by Ko et al. [94]. In this model, two-phase species transport through the porous components of a DMFC was formulated based on Maxwell–Stefan multicomponent diffusion equations while capillary-induced liquid flow in the porous media was described by Darcy's equation. The developed model was also validated against readily available experimental data in the literature. Then, a parametric study was carried out to investigate the effects of the operating temperature, methanol feed concentration, and properties of the backing layer. The results of the numerical simulation clarified that the material properties and design of the anode backing layer play a critical role in the use of highly concentrated methanol fuel in DMFCs.

Wilhelm et al. [95] described the energy storage characterization for a direct methanol fuel cell (DMFC) hybrid system for light traction applications. They evaluated for energy density and power density for energy storage. These are influenced by the operating states of the vehicle as well as the highly fluctuating load profile. For this kind of application a high energy density as well as a high power density is needed. They also analyzed for super capacitor and batteries as suitable alternatives. They developed five different tests to characterize the battery in terms of energy content, high power capability during charge and discharge, thermal behavior and lifetime. The tests showed that all batteries have to be operated on a partial state of charge (pSOC) and a thermal management is very important. Finally they identified that, lithium battery was the suitable energy storage for the considered application.

Xu et al. [96] worked for direct methanol fuel cells operation with highly concentrated methanol. In this work, they tested a direct methanol fuel cell (DMFC) to operate with highly concentrated methanol with an anode flow field. The basic idea of this flow field design was to vaporize methanol solution in the flow field by utilizing the heat generated from the fuel cell so that the methanol concentration in the anode catalyst layer can be controlled to an appropriate level. The flow field was composed of two parallel flow channel plates, separated with a gap. The test results showed that this unique flow field design enables the DMFC operating with 16.0-M methanol to yield a power output similar to that with the conventional flow field design with 2.0-M methanol, significantly increasing the specific energy of the DMFC system. They also investigated the effects of methanol solution flow rates and operating temperature on cell performance.

The fabrication and performance evaluation for a novel small planar passive direct methanol fuel cell (DMFC) stack was also carried by Feng et al. [97]. In this work, several practical operating performances were evaluated with a novel small passive direct methanol fuel cell (DMFC) stack in different potential application conditions. The combination with DC–DC convertor, the fuel cell can realize a much more stable constant voltage output and along with super capacitors, it can provide a large current pulse discharge. They noticed that after increasing the operating time, the methanol crossover and produced water at the cathode could cause the fuel cell performance degradation.

Barton and Rupert [98] studied for UK energy supply pathways for reduction of greenhouse gas emissions by 80% by 2050, and substantially reduce reliance on oil and gas while maintaining a stable electricity grid and meeting the energy needs of a modern economy. They found that hydrogen use in the transport sector is important in reducing distributed carbon emissions that cannot easily be mitigated by carbon capture and storage (CCS).

Hamada et al. [99] also describes the field experiments and numerical simulations on hybrid utilization of renewable energy and fuel cells. The used solar energy and fuel cells for electric power and domestic hot water supply in residential buildings. Through this system, they achieved a large amount of reduction in primary energy consumption compared with conventional systems. The simulation results of the system showed that the annual percent reductions in energy for combined use of a SC and FC were 26–28%. For combined use of a photovoltaic (PV) and FC, the calculated annual percent reduction in energy was very high, ranging from 43% to 66%.

### 3.3. Pumped hydro energy storage systems (PHESS)

Among the other available commercial technologies, pumped hydro electric storage is the oldest and largest available energy storage technology. The general configuration in this case involves water storage facilities at two different elevations. They can either be natural or artificially constructed, and can have a wide range of size. They could include underground caverns, old mine shafts, volumes formerly occupied by oil, or newly excavated volume. These schemes consist of two large reservoirs at different levels with a store of water. To store energy off-peak, electricity is exploited to pump water up to the top reservoir. The collected water can then be discharged to a lower reservoir at the other end of a height differential. This flow of water drives turbines in the same way as hydroelectric dams [53,100].

Water can be run through turbines from the upper reservoir to the lower one and hence produces electricity. But then water can be pumped back up to the storage area at the higher elevation, effectively recharging the system. In this case, it is also possible to use two-way turbines. Fig. 35 shows a typical hydro-pumped system in which the water is pumped to the higher level reservoir through the power tunnel and when there is a need to use this water the control room issues the order of intake shaft opening. The water goes through the channel into the turbine and then returns back to the source (lake) through the tailrace tunnel.

This technology can provide reliable power within a short period of time (typically within 1 min) when required. The efficiency of pumped hydro is in the range of 70–85%. From the total worldwide hydro-pumped generation capacity about 3%, there is approximately 90 GW of pumped storage in operation. In Japan, research is being undertaken using the concept at the coast whilst it is also theoretically possible to use old mineshafts. A limiting factor to pumped hydro is the large capital costs involved in construction. For example, the 1080 MW goldisthal plant in Germany cost $700 million in 2002. This can make sense if the price of electricity varies significantly at different times of the day or the week. This type of energy storage can be especially useful in connection with daily peak shaving and load leveling as well as weekly and seasonal variations in the energy demand. The large pumped hydro storage systems in some countries around the world are listed based on their capacities in Table 10 [100].

Construction of hydro-pumped sites creates some potential problems regarding damaging the environment. Using old mineshafts or coastal locations may present opportunities at locations

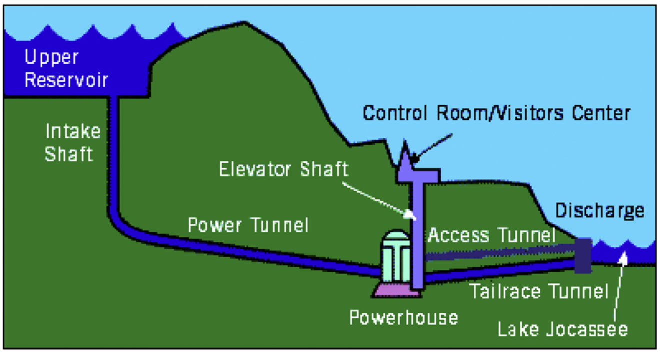



**Fig. 35.** General configuration of a PHES.

**Table 10**
Examples of large pumped hydro systems [53].

| Country | Name | Capacity (MW) |
|---|---|---|
| Argentina | Rio Grande-Cerro Pelado | 750 |
| Australia | Tumut Three | 1500 |
| Austria | Malta-Haupstufe | 730 |
| Bulgaria | PAVEC Chaira | 864 |
| China | Guangzhou | 2400 |
| France | Montezic | 920 |
| Germany | Goldisthal | 1060 |
| | Markersbach | 1050 |
| India | Purulia | 900 |
| Iran | Siah Bisheh | 1140 |
| Italy | Chiotas | 1184 |
| Japan | Kannagawa | 2700 |
| Russia | Zagorsk | 1320 |
| Switzerland | Lac des Dix | 2099 |
| Taiwan | Mingtan | 1620 |
| United Kingdom | Dinorwing Wales | 1728 |
| United States | Castaic Dam | 1566 |
| | Pyramid Lake | 1495 |
| | Mount Elbert | 1212 |
| | Northfield Mountain | 1080 |
| | Ludington | 1872 |
| | Mt. Hope | 2000 |
| | Blenheim-Gilboa | 1200 |
| | Raccoon Mounain | 1530 |
| | Bath County | 2710 |

previously not considered. Many areas that are potentially suitable to establish a hydro-pumped site can cause severe environmental risks for ecosystems and fragile highland areas, which may often be located within National Parks.

### 3.3.1. Pumped hydro energy storage systems applications

Energy storage constitutes an effective way to manage excess RES production, and pumped storage is a suitable and mature solution for large storage capacities. Pumped hydroelectric energy storage (PHES) is the largest and most mature form of energy storage currently available. PHES is a well-established technology for large-scale storage of electricity.

As concerns about global warming grow, societies are increasingly turning to the use of intermittent renewable energy resources, where energy storage becomes more and more important. PHES is the most established technology for utility-scale electricity storage. Although PHES has continued to be deployed globally, its development in the United States has largely been dormant since the 1990s.

The increasing use of renewable energy technologies for electricity generation, many of which have an unpredictably intermittent nature, will inevitably lead to a greater need for electricity storage. Although there are many existing and emerging storage technologies, most have limitations in terms of geographical constraints, high capital cost or low cycle life, and few are of sufficient scale (in terms of both power and storage capacity) for integration at the transmission and distribution levels.

Connolly et al. [101] developed a computer program to locate potential sites for pumped hydroelectric energy storage. The capital costs required for PHES are high and the availability of suitable sites is decreasing. The aim of this work was to develop a computer program that will scan a terrain and identify if there are any feasible PHES sites on it. They evaluated a program for 20 km $\times$ 40 km area in the South West of Ireland and provided limitations and feasible locations for PHES. Crampes and Moreaux [102] also analyzed for potential of cost saving in pumped storage. They developed a model and provide a simple framework to assess when pumped storage is efficient and when it should be optimally dispatched. In this work, the efficient use of the technology was analyzed based on the given outputs at each period determining the frontier between the storage and no-storage solutions and its sensibility to cost variations. They also suggested that how this optimal use of pumped storage can be implemented in the competition framework sustained by governments in industrialized countries remain to be analyzed.

The opportunities and barriers to pumped-hydro energy storage in the United States were studied by Yang et al. [103]. According to that assessment, the United States has a potential for PHES sites capable of handling $>1000$ GW of power. They also discuss about the many factors which are effecting for PHES development in the United States. The natural gas production from shale formations is also one of them. Increased supply of unconventional natural gas (shale gas) may significantly lower natural gas prices again and render PHES uncompetitive compared to gas for use in peaking power supply. On the other hand, the prospect of a legislated price or cap on carbon dioxide emissions is likely to strengthen the economic outlook of PHES. They also suggested that if PHES will develop properly, it can play an important role in a low-carbon electricity system in the United States.

Steffen [104] proposed pumped hydro storage (PHS) in Germany and analyzes the current development and evaluates the revenue potential as well as possible barriers. In this work, they discussed about the high investment costs, profitability of power plant projects is a general issue in the current German market situation. The result of this work is the future cost of pumping electricity as well as remuneration for grid services are subject to high uncertainty. The realization of the proposed projects might therefore depend on subsidies, and it is worth evaluating the consequences of different capacity subsidy setups for storage plants. While PHS is part of an efficient future generation portfolio, there remain limitations to its function of integrating intermittent renewable generation. Overall, PHS has good potential and the current PHS pipeline allows to significantly increasing German electricity storage capacity by means of a well-proven technology.

Anagnostopoulos and Papantonis [105] investigated the performance of a pumped storage unit introduced in a conventional hydroelectric power plant in Greece. They studied the RE production from pumped hydro storage on the basis of plant operation and the electric grid data for a reference period of one year. They carried out the simulation on the basis of current financial conditions in Greece and investigated the results in detail for energy production. The results showed that a considerable amount of excess RES production can be stored, but the economic viability of the investment depends on some critical parameters like as optimum sizing and operation strategy.

As a partial solution to manage the energy storage technology with the help of wind-powered, pumped hydro energy storage system (PHESS) on the island of Gran Canaria (Canary Islands) was discussed by Padrón et al. [106] They developed the model for two of the largest existing reservoirs on the island used as storage

reservoirs with three 54 MW generators and find that this type of installation can reduce fossil fuel consumption, reducing $CO_2$ emissions. They also found that these systems also have an enormous, unexplored potential within the general guiding framework of policies promoting clean, renewable energy.

The concerned about a relatively new concept which will be referred to here as pumped thermal electricity storage (PTES), and which may be able to make a significant contribution towards future storage needs was highlighted by White et al. [107]. This work was focused on thermodynamic aspects of PTES, including energy and power density, and the various sources of irreversibility and their impact on round-trip efficiency. During charge, PTES makes use of a high temperature ratio heat pump to convert electrical energy into thermal energy which is stored as 'sensible heat' in two thermal reservoirs, one hot and one cold. When required, the thermal energy can be converted back to electricity by effectively running the heat pump backwards as a heat engine. The result indicated that the round-trip efficiency and storage density both increase with the compressor temperature ratio. High temperature ratios, however, imply high pressure ratios which in turn imply high cost for the hot reservoir. This is mitigated by the use of a monatomic gas such as argon for the working fluid.

Connolly et al. [108] discussed about practical operation strategies for PHES utilizing electricity price arbitrage. They studied about three practical operation strategies (24 optimal, 24 prognostic, and 24 historical) and compared to the optimum profit feasible for a PHES facility with a 360 MW pump, 300 MW turbine, and a 2 GWh storage utilizing price arbitrage on 13 electricity spot markets. The results of the study indicated that the almost all (~97%) of the profits can be obtained by a PHES facility when it is optimized using the 24 optimal strategy developed, which optimizes the energy storage based on the day-ahead electricity prices. However, to maximize profits with the 24 optimal strategies, the day-ahead electricity prices must be the actual prices which the PHES facility is charged or the PHES operator must have very accurate price predictions.

Nazari et al. [109] studied for pumped-storage unit potential for energy demand, economics, and environmental constraints. The results of the study showed that pumped-storage and thermal generating units have a potential to minimize the environmental effect. The results show the improvements of 0.03 and 0.50% using the NOM in TC and EXEM, respectively. In addition, they also determined in pumped-storage and thermal unit commitment with considerations for environmental constraints (PSECUC) problem that the PS units can simultaneously decrease the TC and EXEM by 1.20 and 60% respectively.

### *3.4. Supercapacitor energy storage systems (SESSs)*

Capacitors are well-known components which are used commonly in electrical and electronic circuitries. Capacitors can be also used to enhance system stability in power networks. More advanced capacitors are now being developed specifically for energy storage purpose. The classic capacitor comprises two parallel metal plates with an air gap between them. When a voltage is applied across the plates, positive charges are collected on one of the plates and the negative charges are accumulated on the other one [12,21,54].

There are various types of capacitor (Fig. 36) and those are suitable for energy storage and they called electrochemical capacitors (EC). These types consist of a solid electrode and an electrolyte. Charge collects at the interface between the two. These devices, sometimes called supercapacitors, ultra-capacitors or electrical double-layer capacitors (EDLC), can store a very large energy density, probably the highest of any storage device. Ultracapacitors are capable of responding to any changes in power demand in tens to hundreds of milliseconds and are most suited to short-term energy storage applications. The technology is relatively new and there is little cost data available [54].

The energy stored in such a system is proportional to the area and the voltage squared, and inversely proportional to the distance of charge separation. Electrochemical capacitors achieve very high capacitance and energy capacity through very high surface area and very small charge separation distance. Although supercapacitors charge instantly and last longer, batteries can store larger amounts of energy at a given time. SESSs can be charged and discharged hundreds of thousands to millions of times (unlike the battery in your phone, which has about 300 charge/discharge cycles).

Fig. 37 shows a typical supercapacitor which is constructed of two carbonic electrodes and the electrolyte solution between them. During the charge process negative ions are gathered around the positive plate (electrode) losing their electron and positive ions are accumulated on negative electrode absorbing electrons. If the capacitor is disconnected from the source, the difference between the plates potential results in an electromagnetic field. During the discharge the ions return back to their original positions and this fact comes up because of the weakening of the electromagnetic field.

The capacity $C$ can be calculated by Eq. (8).

$$C = \varepsilon \frac{A}{d} \tag{8}$$

where $\varepsilon$ is the permittivity of the material and can be given by Eq. (9).

$$\varepsilon = \varepsilon_r \varepsilon_0 \tag{9}$$

where $\varepsilon_r$ is the relative permittivity of material and $\varepsilon_0$ is the permittivity of vacuum, $8.85 \times 10^{-12}$ F/m. The permittivity was sometimes called the dielectric constant. Hence the stored energy




**Fig. 36.** Some models for different types of supercapacitor [132].

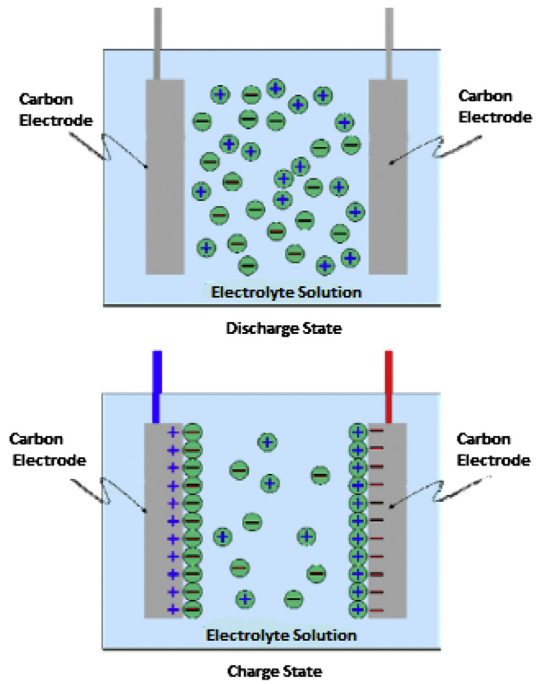



**Fig. 37.** Illustration of charge carrier behavior during both discharge and charge states [132].

in electromagnetic field is computed by Eq. (10).

$$W_C = \frac{1}{2}CV^2 \tag{10}$$

where $V$ is the potential difference between two electrodes.

The capacitor behavior is very dependent to the property (liquid or solid electrolyte) of material used between its two plates. As shown in Fig. 38, the charge is stored in the interfacial region where the electronically conducting material meets the ionically conducting material. The physical separation between the positive and the balancing negative charges is then very small. This can be considered as an equivalent parallel plate capacitor with a thickness of the order of interatomic distances, and results in much greater amounts of charge storage per unit area. Devices with this type of local structure are called electrochemical capacitors, and there are two general types. The first group which is so-called ultracapacitors involves the storage of charge in the electrical double-layer at or near the electrolyte/electronic material interface. Another group which is so-called supercapacitors utilizes the transient additional reversible absorption of atomic species into the crystal structure of the solid electronically conducting electrode. Both of these mechanisms can lead to much larger values of capacitance than capacitors with dielectric materials between their plates discussed above [53].

### 3.4.1. *Supercapacitor energy storage systems applications*

Zhao et al. [110] used carbon nanosheets as the electrode material for supercapacitors. They comprised carbon nanosheets with comprised of 1–7 graphene layers that are predominantly vertically oriented with respect to a substrate. They measured the capacitance of carbon nanosheets by cyclic voltammeter in a standard electrochemical three-electrode cell. This cell also has a platinum counter electrode and a standard mercury/mercurous sulfate reference electrode in 6M$H_2SO_4$ electrolyte. They used a mathematical model to simulate the total possible capacitance of a virtual supercapacitor cell that contains carbon nanosheets as the electrode material and found to be 1.49 × 104 F.

The carbon nanotubes/cobalt sulfide composites as potential high-rate and high-efficiency supercapacitors were discovered by Chen et al. [111]. They prepared carbon nanotube (CNT)/cobalt sulfide (CoS) composites from cobalt nitrate, thioacetamide, and CNTs in the presence of poly (vinylpyrrolidone). CNT/CoS composites were deposited onto fluorine-doped tin oxide glass substrates and then subjected to simple annealing at 300 °C for 0.5 h to fabricate CNT/CoS electrodes. They found that the CNT/CoS composite electrodes can provide higher specific capacitance relative to other reported ones at a scan rate of 100 mV/s. CNT/CoS composite electrodes also provide a power density of 62.4 kW/kg at a constant discharge current density of 217.4 A $g^{-1}$. With such a high-rate capacity and power density, CNT/CoS composite supercapacitors demonstrate great potential as efficient energy storage devices.

Guo et al. [112] also prepared sucrose-based microporous carbons and its application as electrode materials for supercapacitors. The pore size and specific surface area of the electronic materials samples were in the ranges of 0.7–1.2 nm and 178–603 $m^2$/g, respectively. They used Raman spectra to analyzed the intensity of the samples and found that the intensity of the G band was stronger than that of the D band for the samples with carbonization temperatures above 800 °C. They also found that the sample carbonized at 800 °C displayed the highest specific surface area with a main pore size of about 0.75 nm. After the cyclic test, all samples showed a good cycle performance behavior evaluated using both three-electrode and two-electrode cells.

The poly ethylene terephthalate based carbons as electrode material for supercapacitors prepared by García et al. [113]. They observed that poly ethylene terephthalate (PET) derived-activated carbons follow the general trends for highly porous carbons and display specific capacitances at low current density as high as 197 F $g^{-1}$ in 2 M $H_2SO_4$ aqueous electrolyte and 98 F $g^{-1}$ in the aprotic medium 1 M $(C_2H_5)_4NBF_4$/acetonitrile. They also achieved high performance at high current densities which confirms the potential of this type of materials for electrical energy storage.

Garcia et al. [114] also tested carbon supercapacitors for high performance for renewable energy sources. They used resorcinol furaldehyde catalyzed and hexamethylenetetramine (an amine base) with highly pure carbons for supercapacitor electrodes. The results of this study showed that the electrochemical characterization increases in the specific capacitance per unit of surface area that is 18% higher than that of commercial biomass carbons and their synthetic counterparts. The life of the capacitor was also extended to twice that of the commercial brand tested here and has increased power after cycling. They also found that the supercapacitors were made from this synthesis also have electric double layer characteristics as desired in some applications.

A porous wood carbon monolith (m-WCM) with high consistency and large porosity was successfully synthesized by carbonization of poplar wood by Liu et al. [115]. They used Fourier transform infrared spectroscopy for characterization of surface functional groups and surface morphology and microstructure were physically characterized by scanning electron microscopy (SEM). After the long term cycling experiments for 2000 galvanostatic cycles at 10 mA/$cm^2$ the results showed the excellent stability with a reduction of the initial capacitance values of 3%.

Rakhi and Alshareef [116] also worked for enhancement of the energy storage properties of supercapacitors by using the grapheme nanosheets dispersed with metal oxide-loaded carbon nanotubes. They made electrochemical double layer capacitors by use of the composite as the electrode material and aqueous KOH as the electrolyte. They did the comparative performance study of electrochemical of the composite electrodes and pure GNs electrodes and find that fabricated supercapacitor device exhibited excellent cycle life with ~81% of the initial specific capacitance

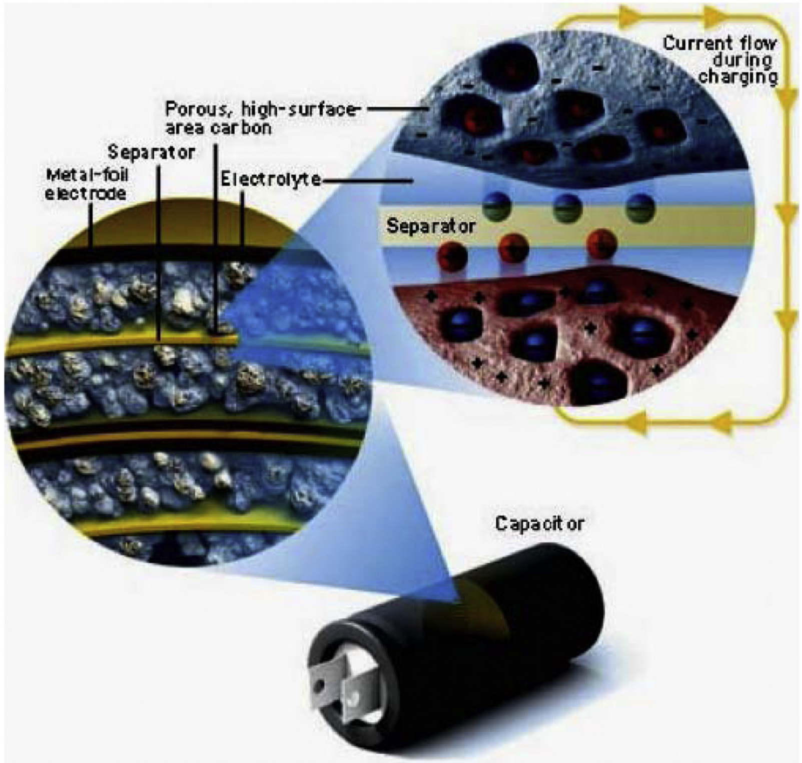



**Fig. 38.** Close-up of physical structure of supercapacitor.

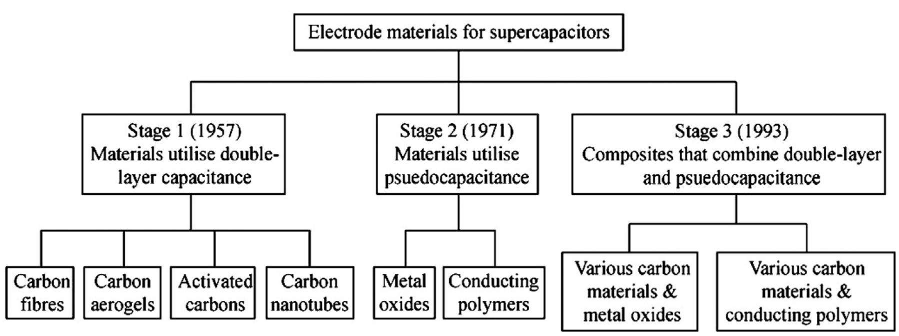



**Fig. 39.** Classification of the supercapacitor materials.

retained after 6000 cycles. They also suggested that the hybrid composite was a promising supercapacitor electrode material.

Peng et al. [117] reviewed for carbon nanotube and conducting polymer composites used for supercapacitors. In this paper, they provided the materials literature which is useful as electrodic materials for supercapacitors (Fig. 39). They found that the electrochemically co-deposited composites are the most homogeneous and show an unusual interaction between the polymer and nanotubes, giving rise to a strengthened electron delocalization and conjugation along the polymer chains. As a result they exhibit excellent electrochemical charge storage properties and fast charge/discharge switching, making them promising electrode materials for high power supercapacitors.

The nickel and cobalt oxide composite as a possible electrode material was used for electrochemical supercapacitors by Wang et al. [118]. In this work, They developed the electrode materials for supercapacitors by synthesized a composite material $Ni_{0.37}Co_{0.63}(OH)_2$ using the chemical precipitation method. The results showed that this material could provide a two-electron redox process accompanied by two $OH^-$ ions. Cyclic voltammogram curves was also recorded for this $Ni_{0.37}Co_{0.63}(OH)_2$ material to measure the specific capacitances at different potential scan rates.

The high performance supercapacitors based on reduced graphene oxide in aqueous and ionic liquid electrolytes were developed by Chen et al. [119]. They investigated the electrochemical properties in the ionic liquid electrolyte and obtained the current density of 0.2 A $g^{-1}$, the maximum capacitance values of 348 and 158 $Fg^{-1}$ in 1 M $H_2SO_4$ and $BMIPF_6$, respectively. Similar study for supercapacitors was also done by Chen et al. [120]. They also used the graphene oxide/polyaniline (GO/PANI) flake composites by coating polyaniline (PANI) onto graphene oxide (GO) sheets for the novel electrode materials. The results of the TGA and CV study showed that both the thermal stability and the electroactivity of the R (GO/PANI) flake composites were distinctly enhanced than those of the GO/PANI composites.

### 3.5. *Compressed air energy storage systems (CAESS)*

CAES refers to a system in which the air is compressed and stored under pressure. The pressurized air can be subsequently released and exploited to generate electricity. From the power

generation perspective, storage of compressed air is meaningful only in conjunction with the gas turbine. Conventional gas turbines which were exploited in aero applications or for power generation consist of two major components, namely, a compressor and a turbine mounted on a single drive shaft [54].

In conventional operation of gas turbines, the air is drawn into the compressor in order to be compressed. This compressed air is then directed into a combustion chamber where it is mixed up with fuel and ignited. To increase the energy content of compressed air, heating can be an effective solution. The hot compressed gas is then released through the machine's turbine blades and results in the rotation of turbine and generation of electricity [54].

Although a gas turbine normally has the compressor and turbine closely integrated, the air compression can be carried out in a separate system and at a different time to power generation. To meet this target, CAES can be utilized in generation of electricity.

In a CAES plant the compressor and the turbine are separated. Both the compressor and the turbine can be separately connected to a motor generator by use of a system of clutches. In storage mode of operation, the compressor stage of the gas turbine is driven by the reversible motor generator using off-peak power from the grid. The product, which is compressed air, is stored in a special cavern. Next time when the power is required, air is released from the cavern into a combustion chamber and mixed up with fuel. Under these conditions the motor generator is used in generation mode to produce electricity. Fig. 40 shows a typical gas turbine system which includes in CAES. In this combination CAES system is run through a separate motor driver and not the same generator connected to the grid [54].

### 3.5.1. *Compressed air energy storage applications*

Compressed air energy storage considered as green energy option and plants are being recognized as technically feasible and economically attractive for load management. The technology in this respect is a mature and reliable bulk energy storage technique with promising potential to accommodate high wind power penetration in power systems [121]. Such a system essentially consists of a power train motor that drives a compressor (to compress the air into the cavern), high pressure turbine, a low pressure turbine and a generator as illustrated in Fig. 41.

Use of compressed air in industry and in service sectors is common as its production and handling are safe and easy. In most Industrial facilities, compressed air is necessary to manufacturing [122]. Compressed air accounts for as much as 10% of industrial electricity consumption in the European Union [123].

A trigeneration system based compressed air and thermal energy storage system was developed by Li et al. [124]. They developed a novel energy storage system which stores excessive energy in the form of compressed air and thermal heat. The cooling power from this system was generated by direct expansion of compressed air instead of the use of absorption chilling technology. In addition, the system can meet the end users' demands for electricity, and heating and cooling powers through controlling the inlet pressure and temperature of an air based expander. The results of this study showed that the comprehensive efficiency of the system is very high (~50%) in winter months when no cooling is needed. In summer months, due to the high power consumption in air compression process and inefficient expansion of the compressed air (for cooling power production) the comprehensive efficiency decreases to about 30%. They found that this system is very promising for practical applications particularly for the use of renewable energy due to good flexibility and simple configuration.

Madlener and Latz [125] completed an economical study for decentralized compressed air energy storage for enhanced grid integration of wind power. They studied for CAES system with 90 MW of compressor and 180 MW of generation capacity. The CAES system was operated independently of the wind park such that profits from peak power sales on the spot market and the reserve power market were maximized. They found that the economics of the systems is depends on how intensively the spot market and the market for minute reserve. They found that CAES plants can be operated economically if government is provided some support. This study also showed that a centralized CAES plant is more attractive than a wind power plant with integrated CAES.

Mason and Archer [126] investigate two different methods of transforming base load electricity from wind via compressed air energy storage. In the former, the electricity from natural gas combined-cycle (NGCC) power plants was used and in the latter, the electricity from compressed air energy storage (CAES) power plants was used. Their study reveals that the combination of wind and NGCC power plants is the lowest-cost method of transforming wind electricity into firm base load capacity power supply as compared to combination of wind and CAES power plants. However, transforming the electricity through second methods, has lowest $CO_2$ emission and lowest fuel consumption. This is an addition environmental benefit.

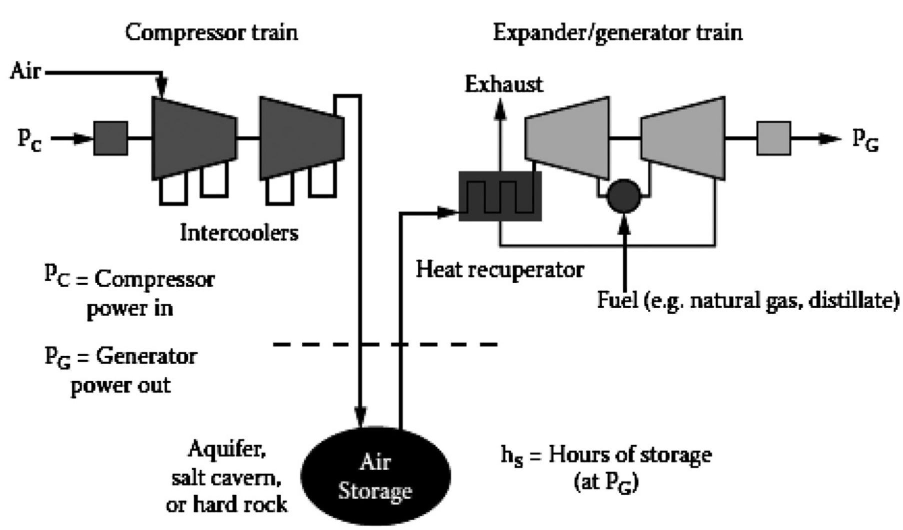



**Fig. 40.** CAES system configuration [68].

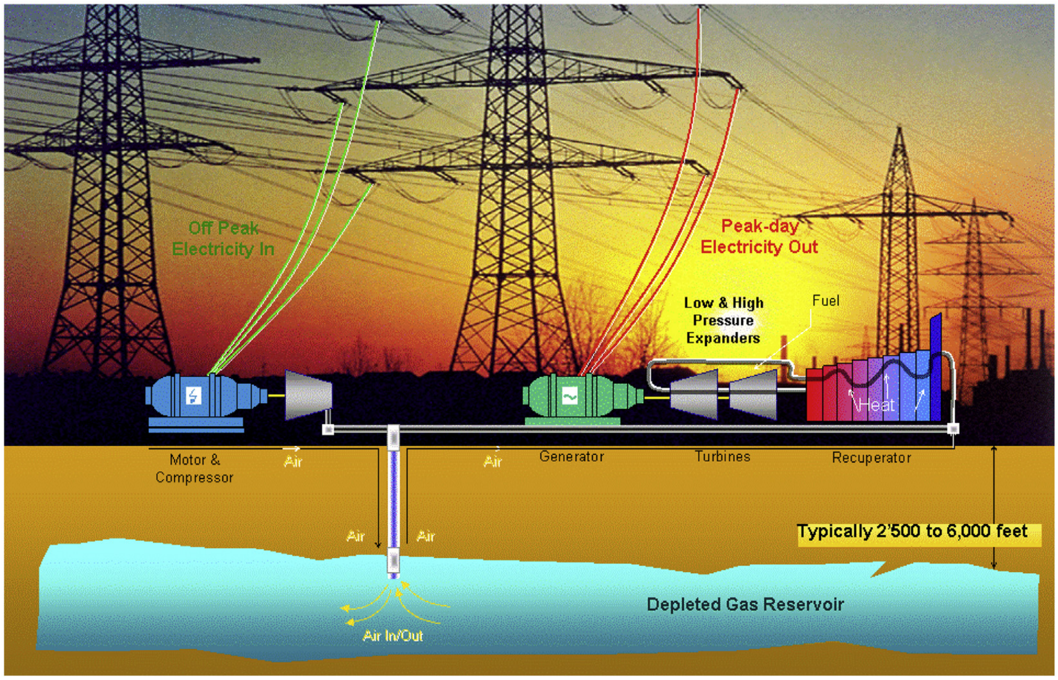



**Fig. 41.** Schematic of compressed air energy storage [131].

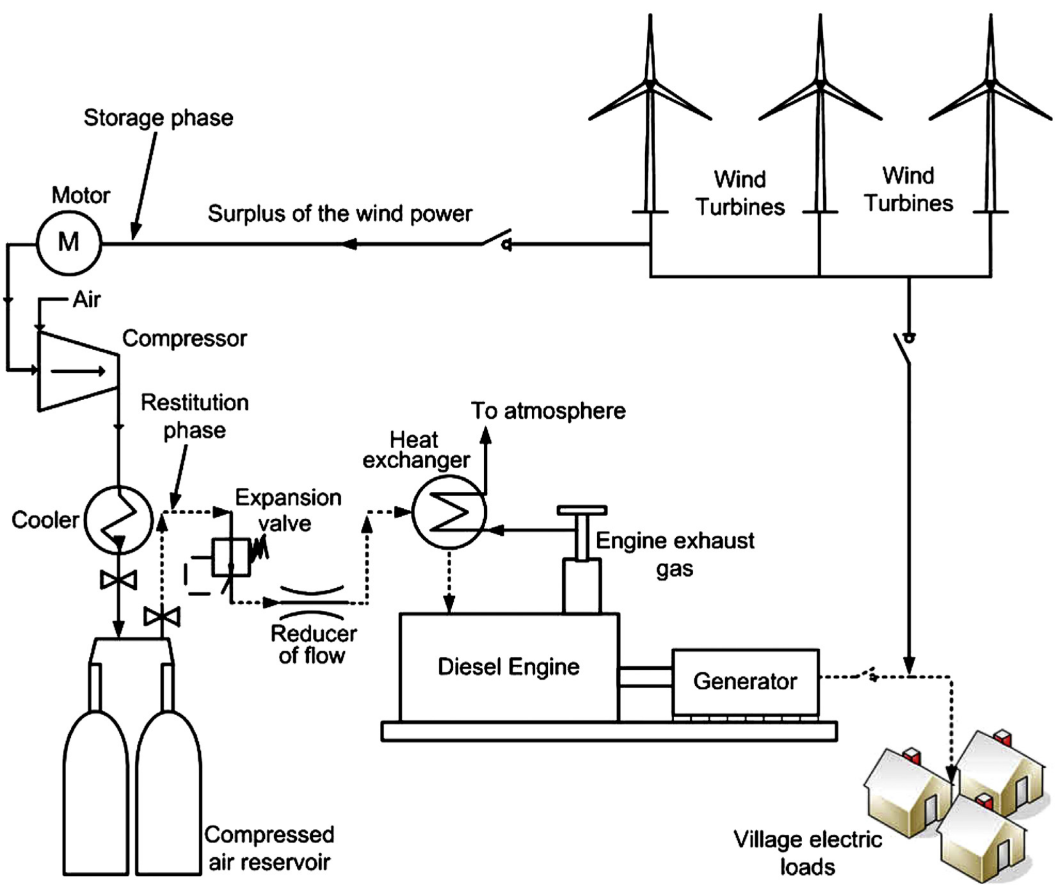



**Fig. 42.** Schematic of hybrid diesel compressed air energy storage power generation [127].

The novel and innovative concept on the hybrid wind–diesel–compressed air energy storage system for remote areas was proposed by Ibrahim et al. [127]. In this hybrid system super-charging, will increase the wind energy penetration rate. The diesel generator works during the periods of low wind velocity, when the wind power is not sufficient to sustain the load. The schematic of proposed hybrid system is illustrated in Fig. 42. The system is in position to cut greenhouse gas released from diesel

based power generation in remote areas. The diesel based power generation systems are expensive and inefficient technology that is responsible for the emission of 1.2 million tons of greenhouse gas (GHG) annually, only in Canada [128].

Garvey [129] studied an integrated approach of compressed air renewable energy system, in which harvests renewable energy directly in the form of compressed air and later converts that to the form of electrical power for transmission. It was examined the viability of storing heat offshore in conjunction with compressed air. In this case, a dispatchable renewable energy system can be devised wherein primary energy harvesters deliver compressed air into a manifold and an expander generator system recovers mechanical power and subsequently electrical power from that air. The schematic of integrated approach of compressed air renewable energy system is presented in Fig. 43.

Jubeh and Najjar [130] proposed a concept of power generation by adoption of adiabatic CAES system. The concept include the stores the heat from the hot compressed air in heat storage before the air enters the cavern. In discharge mode the air flows through the heat storage again and is heated up to the turbine inlet temperature without fuel consumption. This system uses heat storage as a central element of the plant. The heat is supplied to the expansion process if needed otherwise rejected compression heat and thus to avoid a gas combustor. During the charge period the heat is extracted from the air stream and stored. When energy is required by the grid, the compressed air and heat energy is recombined and expanded through an air turbine as illustrated in Fig. 44. The whole system is $CO_2$ free.

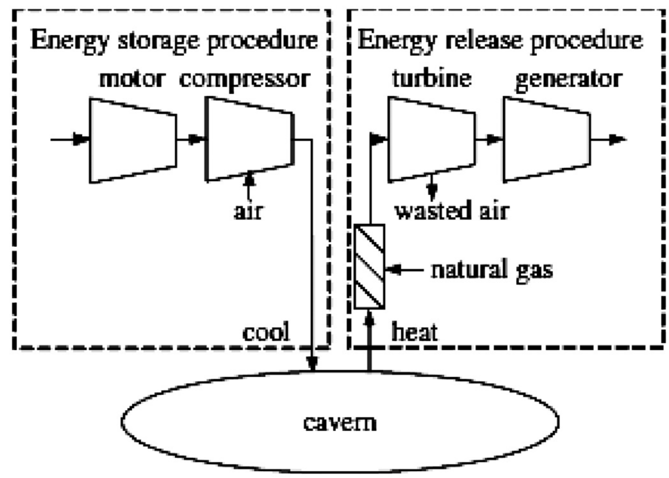



**Fig. 45.** A mature CAES structure [121].

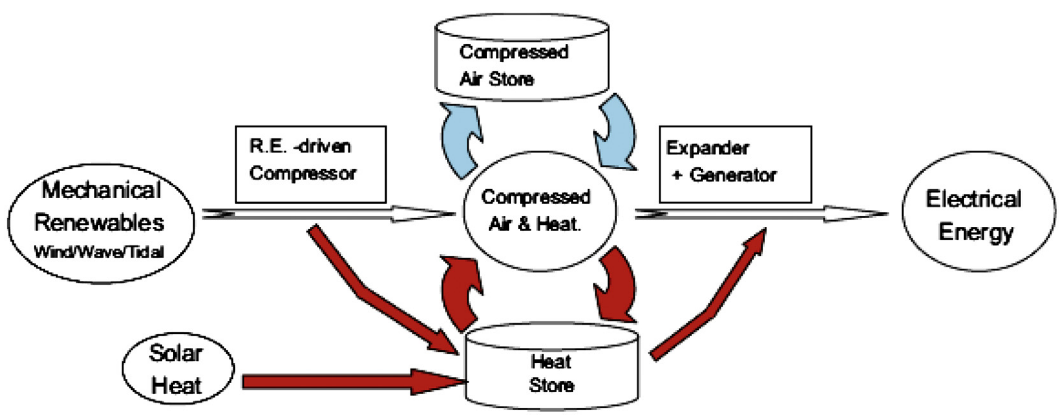



**Fig. 43.** Integrated compressed air renewable energy systems [129].

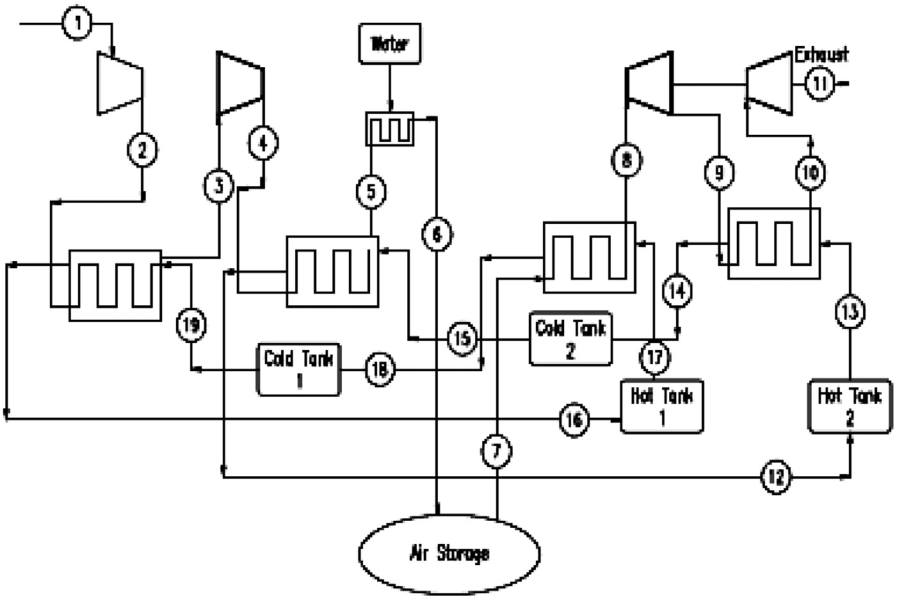



**Fig. 44.** Adiabatic CAES power generation system [130].

Wang and Yu [121] proposed optimization model to decide the rated power and capacity of a CAES system, which is crucial to maximizing economical profits (Fig. 45). The model was tested a case study of a 19-bus power system containing 8 wind farms, model reveals that CAES stakeholders can take advantage of temporal arbitrage and the ability to recover wind power curtailment, indicating that CAES is economically feasible under base case operation. Moreover, CAES can reduce the system's carbon dioxide emissions significantly. If a carbon compensation policy is adopted, CAES stakeholders can realize additional profits from the environmental protection of CAES.

## 4. Conclusion

The global growth in using renewable energy resources to generate the electricity, at the same time, leads to an ever growing trend for the application of energy storage devices in power networks. To design smart grids, the role of ESS would be really prominent since both economics and dynamics of whole power network can be impressed where ESSs are utilized. The presence of ESSs in intelligent micropower grids converts the non-dispatchable RESs to dispatchable power generation units and hence makes the whole system robust and reliable. In this paper, the technical advantages of using ESSs are well-presented where the main issues are the power system planning, stability and quality. The technological and physical properties of energy storage devices are also discussed with details.

## Acknowledgment

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